ELECTRICAL ENGINEERING

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FOR ELECTRIC LIGHT AND POWER ARTISANS AND STUDENTS

(EMBRACING THOSE BRANCHES PRESCRIBED IN THE SYLLABUS ISSUED BY THE CITY AND GUILDS TECHNICAL INSTITUTE)

BY W. SLINGO AND A. BROOKER

WITH 389 ILLUSTRATIONS

NEW EDITION THOROUGHLY REVISED BY W. SLINGO
ASSISTED BY T. F. WALL, M.Sc.

LONGMANS, GREEN, AND CO.
39 PATERNOSTER ROW, LONDON
NEW YORK, BOMBAY, AND CALCUTTA
1908

BIBLIOGRAPHICAL NOTE.

First Edition, March 1890; *Reprinted May* 1890, *September* 1891, *December* 1891, *June* 1893; *New and Revised Edition, January* 1895; *Revised and Enlarged Edition, October* 1898; *Revised Edition, November* 1900; *New Edition, February* 1903; *Revised, June* 1908.

NOTE TO THE REVISED EDITION

This work has again been thoroughly revised, and considerable effort has been made to bring the book once more into line with current practice. Electrical Engineering has, however, made such strides during the past few years that it is now a much more difficult matter than when this book was first written to satisfactorily cover the whole field in a single volume. Instead of making extensive sacrifices in the fundamental parts of the subject, in order to obtain space to mention every branch, important or unimportant, of Electrical Engineering, we have striven as heretofore to enable the student to obtain a perfectly sound knowledge of direct and alternating currents, the machinery and apparatus connected therewith, and the more important applications thereof. It will, perhaps, be noticed that certain appliances, such as open coil dynamos, which are now obsolescent, and in fact almost obsolete, have been allowed to remain. This course has been followed for two reasons, the first being that they afford useful object lessons in the development of the subject, and the second that, although the manufacturer regards them as things of the past, there are still many examples in actual use.

We are glad that it has not been found necessary to alter either the character or the general arrangement of the book, circumstances which have enabled us to continue to aim at simplicity in language and clearness in definition in order to make the student's progress easy, pleasant, and certain.

June 1908.

PREFACE

TO

THE FIRST EDITION

We have frequently been asked by artisans and students to recommend a single work covering the whole field of Electric Lighting. Our inability to comply with this request has prompted us to endeavour to fill such a palpable gap in the literature of technical science. We have designed this book to cover the extensive syllabus of the City and Guilds of London Institute, and have so enlarged its scope as to make it embrace the requirements not only of those actually employed in the electric lighting industry, but also of those who, while having little or no electrical knowledge, have under their supervision various kinds of electrical machinery. The work should therefore prove of service to such men as marine, railway, and tramway engineers, naval officers, municipal officials, and managers of mines and factories.

We recognise to the full the fact that, as a rule, the most successful electrical engineers are evolved from good mechanical engineers, and have striven to give our readers, even though they may possess no previous electrical knowledge, a clear insight into the purely scientific as well as the practical part of the subject. Every effort has, however, been made to embrace only the essential branches of the pure science, omitting those which, while interesting and serviceable in other fields, are not required in electric lighting or the electrical transmission of power. It is hoped also that we have succeeded in the difficult task of explaining the subject clearly and in simple language. The close connection between the three kinds of electrical phenomena, static or

frictional, dynamic or current, and magnetic, has been carefully explained and made to follow naturally. It is believed that the fact that magnetism is primarily but a consequence of dynamic electricity, or the more or less permanent effect on certain substances of an electrical disturbance, instead of being a separate and distinct series of phenomena, has not hitherto been so plainly and unhesitatingly expressed. It is our firm conviction that, in the near future, this view of the question is the one which will be universally adopted. The conception of 'lines of force' is one of great value to the student, and he will find them here reasoned about as having a tangible existence. It would be impossible to describe every piece of apparatus or machinery in actual use, and we have selected those which, while having proved in practice to be among the best in their respective classes, also serve to illustrate in the clearest manner the laws and principles involved. In a few cases, however, the apparatus can scarcely be said to have been successfully applied, but they have been introduced as indicating the highest present developments in directions in which success will probably be attained.

Although primary batteries are not used to any great extent in electric lighting, except for testing and other similar operations, yet a considerable amount of space has been devoted to them, and to the experiments which can readily be performed by their aid, because long experience has taught us that they afford in the readiest way a clear insight into the fundamental principles of the science and the various laws so far discovered.

An unusually large number of the explanations have been based upon Ohm's law and its consequences. Mathematical formulæ and explanations have, where possible, been avoided; where they do occur they are invariably simple, and are generally accompanied by arithmetical examples. As they merely supplement the ordinary explanations, they can usually be ignored without the meaning being missed; but those able to solve a simple equation will find very little indeed which cannot easily be followed.

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ELECTRICAL ENGINEERING

CHAPTER I

CURRENT—POTENTIAL—CAPACITY—CONDUCTORS—INSULATORS

When a stick of sealing-wax is rubbed with a piece of dry fur or flannel, the wax acquires the power of attracting to itself any light substances that may be in its vicinity. By taking suitable precautions a like power can be detected in the fur or flannel. Similar phenomena can also be produced by the rubbing together of other substances, such as glass and silk, indiarubber and silk, brown paper and a bristle clothes-brush. A body which exhibits this power of attraction is said to be endowed or charged with electricity, or to be electrified.

But there are two electrical states, and this can be easily proved; for if by means of a foot or so of silk ribbon we suspend the electrified sealing-wax and bring near it another electrified stick of sealing-wax, repulsion ensues—that is to say, the suspended rod recedes from the approaching one. On the other hand, if certain necessary precautions have been taken to prevent the neutralisation or escape of the electricity that was generated on the fur or flannel rubber, it will be seen that, on bringing it near the suspended sealing-wax, attraction takes place. A similar result would follow if a warm glass rod were rubbed with a piece of dry silk and then brought near the sealing-wax. On suspending, however, the electrified glass and bringing the electrified fur near it, repulsion would take place. It is manifest, then, that as electrified glass attracts electrified sealing-wax, but is repelled by or repels electrified fur, there are two electrical states, one on the

sealing-wax, which is called negative, and the other on the fur, which is called positive. It is also clear that bodies similarly electrified are mutually repellent, while bodies dissimilarly electrified are mutually attractive. This matter will again be referred to, but the points to which especial attention is now directed are, first, that whenever any two bodies are rubbed together, the positive electrification developed on the one body is always equal in amount to the negative electrification on the other; and, secondly, that the amount of electrification developed by rubbing the two bodies—say sealing-wax and fur—together bears no direct relation to the amount of actual friction to which the bodies are subjected, for what appears to be really essential in order to obtain the highest possible degree of electrification is to bring every portion of the one surface into intimate contact with every superficial particle of the other, and when that is done, no extra amount of rubbing or friction can develop any further degree of electrification.

Speaking generally, then, it may be said that when any two bodies are rubbed together electricity is produced, although it frequently happens that the amount is so small as to render its detection very difficult. If, however, delicate apparatus, which we will not pause here to describe, be employed, very feeble charges can be indicated. In fact, if a piece of zinc and a piece of copper are simply placed in contact, the feeble charge of electricity then developed can be rendered evident. If the same pieces of metal are dipped in saline or acidulated water, without being allowed to touch each other, a similar result follows, although in this case the water itself becomes an important factor in determining the resultant electrification. The end of the zinc outside the liquid will be found to possess properties similar to those of the sealing-wax after it has been rubbed with fur. It is, therefore, said to be negatively electrified. The copper, on the other hand, will have an electrical state similar to that of the fur itself, or of the glass which has been rubbed with silk, and it is therefore said to be positively electrified.

It follows that whether the manifestation of electricity is the result of so-called friction, whether it is a consequence of the simple contact of two dissimilar bodies, or whether it is the result

of some physical or chemical change, it is with precisely the same phenomena that we have to deal. As we shall learn later on, electrification may be set up in a variety of other ways, but the law of equal positive and negative electrification always holds good.

It may be accepted as a general fact that when the same kind of force is bestowed upon two adjacent points or bodies, but to a different extent in the one case as compared with the other, there is a universal tendency to equalise the distribution of the force—that is to say, to produce equilibrium; and this equilibrium will always be established when the conditions become such as to render it possible. Reverting again to the zinc and copper plates partly immersed in water, the exposed ends will be electrified differently, and there will in consequence be a tendency to produce equilibrium, or, as it is more generally called, neutralisation. This will be aceomplished if the necessary facilities are afforded, and until this is done the intervening space will be subjected to what may be called an electrical stress, resulting from the effort to effect neutralisation. It is found by experiment that a piece of metal affords the readiest means of relieving the strain due to this stress, thus facilitating neutralisation, for on joining the two plates together, say by a piece of copper wire, a momentary rush of electricity from the one to the other will take place. This phenomenon is that which is generally known as discharge and it affects the whole combination, including the liquid and the metal surfaces in contact with it.

This brief spasmodic flow or rush of electricity, whose function it is to restore the electrical equilibrium, causes, however, a series of chemical changes to take place in the liquid itself, among other things a portion of the zinc being dissolved and converted into what is called a salt of that metal. These chemical reactions cause in their turn a fresh electrical difference between the plates, which is followed immediately by another equilibrating flow, and that by a further electrical difference, and so on. The changes follow one another in exceedingly rapid succession—so rapid, in fact, that it is a matter of impossibility to distinguish them separately, and we have consequently what appears to us as, and what is known as, a continuous 'current' of electricity.

A little reflection will make it evident that by following out the line of experiment and deductions here indicated the so-called single and double fluid theories of electricity may both be disregarded; they are unnecessary and involve considerations and concessions which are not warranted by the circumstances. In point of fact, electricity is not a fluid at all, and only in a few of its attributes is it at all comparable to a fluid.

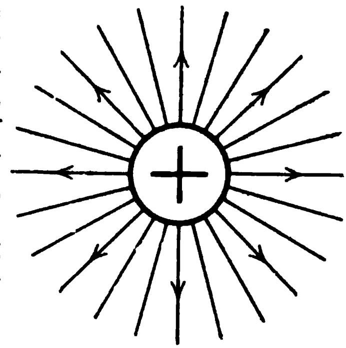
Let us rather consider electricity to be simply a manifestation of energy which imparts to material substances a peculiar state or condition, and that *all* such substances partake more or less of this condition, just as we say that all bodies are heated, although to varying degrees, and that in virtue of this heat their particles are set into more or less rapid vibration.

Moreover, as in the case of a heated body, there is a region surrounding an electrified body in which the force due to the tendency to produce electrical equilibrium can be made evident This is shown by the fact already referred to, that two bodies in a similar electrical state repel one another, while others in different electrical states attract. It is inconceivable that such an effect as the imparting of motion to a mass of matter can be produced without the aid of some medium capable of transmitting the force. What this medium actually is is a matter of doubt, and so also is the mode or method of transmission. In such circumstances it becomes convenient to picture to ourselves the propagation by means of *lines of force*, traversing an infinitely elastic, imponderable medium, or substance, as it is sometimes called, which is assumed to pervade all matter and all space, and which is known as 'ether.' Even though these lines of force may have no actual existence, the conception is, nevertheless, exceedingly useful, and facilitates an accurate estimation of the way in which electrical phenomena are set up, so much so that the idea imperceptibly grows upon the student, and to him the lines of force become endowed with a definite meaning.

There are three features about these lines of force to which we may draw attention. In the first place, their assumed position indicates the path along which the action takes place; secondly, their direction in this path indicates the direction in which the

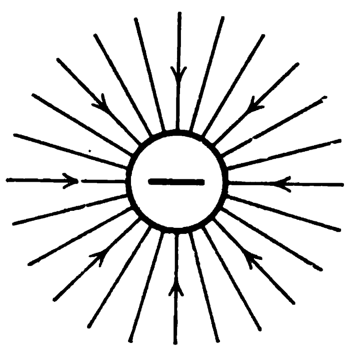
force is transmitted; and, thirdly, their density, or the number occupying a given space, measures the strength or magnitude of the force. Having given to these lines of force position, direction, and density, we can predict the result which should follow in any given electrified region or electrical field. For the action is always such as would result if the lines of force universally tended to coincide in direction, and then to shorten themselves, the magnitude of the action being simply dependent upon the density of the lines.

FIG. 1



In the case of an electrified sphere suspended somewhere in space and remote from every disturbing element, the lines of force would be radial and equidistant in position, their density at any point would depend upon the degree of the electrification or the quantity of the charge, while their direction—that is, radially inwards or radially outwards—would depend upon whether the charge were negative or positive.

FIG. 2

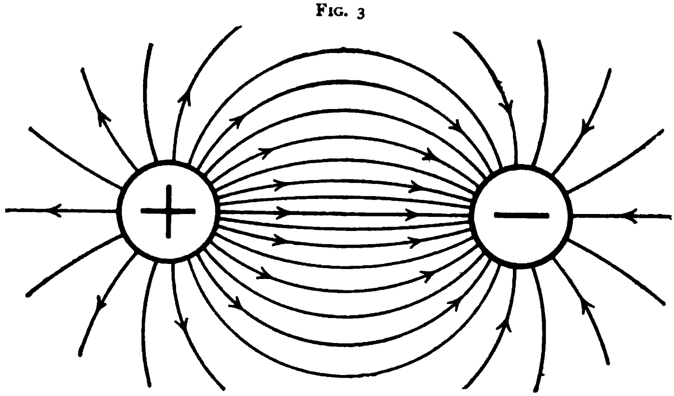


Let us assume a positively charged sphere (fig. 1) to be suspended, with its lines of force directed outwards, and a second sphere, negatively charged (fig. 2), with its inwardly directed lines of force, to be brought into the vicinity of the first sphere. In consequence of the tendency to coincide in direction, many of the lines of force of the two spheres will bend or turn round and concentrate themselves within the space intervening between the spheres in the manner shown in fig. 3. These lines of force will

now be similar in direction, and, owing to the shortening tendency above referred to, attraction results.

The attraction, presuming it to be sufficiently strong, will impart motion to one or both of the spheres, or, in other words, work will be performed. Now, this capacity for doing work arises solely from the electrification, and the quantity of work performed is proportional to the degree of electrification. But 'capacity for doing work' and 'potential' are convertible terms—that is to say, anything which possesses the capacity for doing work may be said to have a certain amount of potential energy ; consequently the degree of electrification of any body is known as its electrical potential.

FIG. 3



We have previously said that the tendency to produce, between two electrified points or bodies, a state of electrical equilibrium is proportional to the difference of their degrees of electrification. In technical language this is expressed as being proportional to their difference of electrical potential. Therefore in the case of the zinc and copper plates immersed in acidulated water, the flow of electricity from the exposed end of the copper, through the connecting wire to the exposed end of the zinc, is correctly described as being due to a difference of potential between those ends.

If the student has grasped what has already been said, he will be able to readily apply the doctrine of potential to special cases ; for example, it will be evident that no two parts of the same body

(providing it be one that can transmit or propagate the flow of electricity) can remain for any length of time at different potentials; for directly a difference of potential is established an electrical stress is set up, and the flow of electricity follows as a natural consequence. On the other hand, where there is no difference of potential there can be no flow of electricity. So that we come to these conclusions—viz. that electricity always flows or tends to flow between two bodies which are at different potentials; that it flows from the body possessing the higher to that possessing the lower potential; that in the case of the 'current' maintained by the 'simple cell,' composed of zinc and copper plates dipping into acidulated water and referred to in a previous page, we had a difference of potential established on the zinc and copper extremities; that on joining these extremities together there was a flow of electricity to produce equilibrium; that this, by means of the chemical changes, re-established a potential difference; and that these actions and reactions, being alternated with almost infinite rapidity, appear to us as a continuous current.

We may, therefore, in such a case define a 'current' as the expression of an effort ever being made to establish electrical equilibrium between two points which are ever being electrified to different potentials. Neither of these objects is attained—that is to say, a difference of potential is never permanently established on the one hand, and, on the other, equilibrium is never maintained.

Let us further consider the case of the simple cell, the zinc and copper of which, however, instead of being joined together, are each connected to long pieces of wire, whose other or free extremities are inserted in the earth at different places. It used to be the general assumption that in such a case the current would flow from the copper plate to the earth, and through the earth to the other wire, up which it would pass and so return by the zinc plate to the cell. But this hypothesis is altogether uncalled for, more particularly when the distance between the two earth connections is considerable, and only involves the student in unnecessary difficulties. Like everything else in the universe, the earth itself is always more or less electrified, and, as a consequence,

any point on its surface is always at a certain but unfixed potential. It will therefore be seen that, were a body which had been electrified to a higher potential than the earth to be connected with the earth, a flow of electricity would take place passing from that body to the earth, so that both the body and earth assume or strive to assume the same potential, and the passage of this flow could be easily observed by the introduction of certain apparatus. On the other hand, were a body to be electrified to a potential lower than that of the earth and to be connected with it, a flow of electricity would be determined from the earth to the body, and the passage of this electricity could also be rendered evident. Consequently, when copper and zinc strips are immersed in acidulated water so that the exposed ends become electrified, the one to a higher and the other to a lower potential than the earth, the connection of those extremities with the earth causes a flow of electricity from the strip which is at a higher potential to the earth, and from the earth to the strip at the lower potential, and this will be equivalent to joining the plates directly together and so releasing the electrical stress.

Thus it is with every battery so connected: the potential of the earth is above that of one end of the battery and below that of the other end. There is, then, no need for a current to flow between the two earth connections, and the assumption of such a state of affairs is quite gratuitous. It must not, however, be supposed that the flow of electricity from or to the earth can under ordinary circumstances sensibly affect its charge or potential, the terrestrial charge as a whole being so enormous as to make any other charge incomparably feeble and insignificant. To make this clearer we will employ an analogy. Let us suppose that we have two tanks, one (A, fig. 4) containing water, and placed above the level of the ocean (C D), the other (B) which we will suppose to be empty and partly immersed below the ocean level. If now we suppose holes to be made in the bottoms of the tanks, all the water will flow out of the higher tank into the sea below, while water will flow up into the lower one until the ocean level is reached. But of course no one would contend that these changes would make any difference in the level of the surrounding waters, even if more water were received from the higher tank than was

given to the lower; and what is true in this case is equally true in the case of electricity. In fact, the earth is a body whose capacity for electricity, so far as we are concerned, is infinite, and nothing that we can do can appreciably affect its total charge. The contention that when one end of a battery is joined to earth, say, in London, and the other end is joined to earth, say, at Aberdeen, a current flows through the earth from one connection to the other, involves the assumption that these two points, in London and Aberdeen, are thereby placed at different electrical potentials. It would be as reasonable to contend that if we turn on a water-tap into the Thames at London and dig a hole in the bank of the

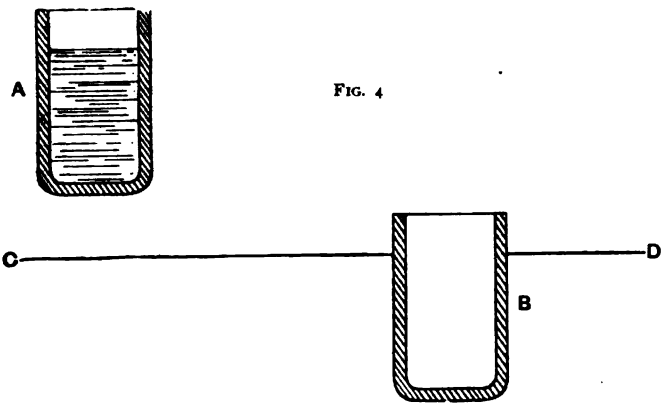


FIG. 4

river at Windsor, we set up a difference of level between the two places, and cause the water which we pour in at London to travel up against the stream and fall out at Windsor. It would also have to be conceded that when we reverse the battery connections, we at the same time make the potential at, say, London, alternately higher and lower than that at, say, Aberdeen. In the special case, however, where a *very heavy* current is passing from the earth at one end of the line and to the earth at the other, the two earth connections being comparatively close together, as might happen in the case of an electric railway, it is of course possible for a considerable portion of the current to actually flow through the earth from one connection to the other, especially if

the substratum be dry, and therefore a bad conductor. Manifestly this would be a very bad state of affairs, indicating that sufficiently good earth has not been made at the ends of the line, and that therefore a considerable amount of energy is being wasted. Reference was made on the preceding page to the capacity of the earth for electricity, and it should be noted that when electricity is communicated to a body, the electrical potential of that body is raised, the extent to which it is raised being dependent upon the amount of electricity communicated, the shape and dimensions of the body, the facilities which the body offers for the electrical distribution through it, and finally upon the relative proximity of other bodies. We may for our present purpose assume that the body to be charged is of metal, that it is suspended in space remote from every other conductor, and that its shape is spherical. In such circumstances a charge communicated to it will be distributed uniformly over its surface, and that charge will raise the potential to a certain value. If we double the amount of electricity communicated to the sphere, the amount of electricity in any particular portion or area of the surface will likewise be doubled. If, however, we increase the radius of the sphere a larger quantity of electricity will be required to raise its potential to any given value. The property, if we may so call it, of requiring a certain amount of electricity to raise the potential of a body to a particular value is known as its electrical or its electrostatic 'capacity.' The larger the body the greater is its capacity, just in the same way that a large tank requires more water than a small one in order to raise the level of the water to a given point.

We come now to a real difficulty—and that is, to be able to say with certainty in which direction a current really travels, or, in other words, to declare which of two differently electrified bodies has the higher, and which the lower, potential. All we can say with any certainty is that there is a difference of potential, and that therefore the current flows from the point of higher to that of lower potential. From a practical point of view it matters little which is the higher, the so-called positive, or the so-called negative, and as this point is immaterial, it is convenient and usual to assume, in the present incomplete and imperfect state of

our knowledge concerning the nature and propagation of electricity, that the electric state which we know as positive has a higher potential than that state which we know as negative, whence we say, or assume, that electricity flows *from* a positively electrified *to* a negatively electrified body. We will in this work follow this assumption, as it involves no sacrifice of principles, notwithstanding the fact that experiments have been performed which tend to show that that state which we call negative is really of higher potential than that which we call positive.

Reference has several times been made to the use of wire as a means of connection between two oppositely electrified bodies, or between two bodies at different potentials. Were we desirous of transmitting mechanical instead of electrical energy, a hempen, or silken cord would answer equally well, if due provision had been made that the cord should have the requisite mechanical strength or tenacity to transmit the energy without fracture. But tenacity is not the necessary attribute for a body to possess in order that electricity may be readily transmitted through it. All substances admit of this transmission, although in very varying degrees. A piece of copper wire offers greater facilities than a piece of iron wire of similar dimensions, which in turn offers yet greater facilities than a similar piece of German-silver wire. But the metals, one and all, are enormously superior in this respect to the great bulk of non-metallic substances. On the other hand, every substance, whatever its nature, offers a greater or less amount of 'resistance' to the transmission of electricity. Bodies which offer little resistance to the electric flow are said to be good conductors, while those which offer considerable resistance are said to be bad conductors or insulators. To the former class belong the metals, carbon, ordinary water, &c., while the latter class includes such substances as glass, air, sulphur, resin, indiarubber, and ebonite. Between these two classes are many substances which might be included in either class, and consequently no hard-and-fast line can be drawn.

It has been shown that the result of joining directly together two bodies electrified to different potentials is a flow of electricity from the body charged to the higher potential to that charged to the lower potential until electrical equilibrium between the two

bodies is obtained. And a similar result follows if we join the bodies together by a piece of wire; while if they have only air or some other bad-conducting substance separating them, there will be no flow at all, or only a very feeble one. If in any given case the path of the flow is made longer, or more difficult, say by the interposition of a longer or a poorer conductor, it naturally follows that the time which is taken for equilibrium to be restored is lengthened, and the rate of restoration—that is, the strength of the current—is less. But if the potential difference and the quantity of electricity transferred are the same in the two cases, the energy expended in the effort to restore equilibrium is the same.

The result, then, of interposing a substance of poorer conducting power, or, what amounts to the same thing, of higher electrical resistance, between two bodies having a potential difference is to reduce the strength of the flow, or the current, passing from the one to the other. We can find a very simple analogy to this if we suppose two tanks at different heights, one directly above the other, the lower one being empty and the upper one full of water. So long as the bottom of the higher one is intact the resistance to the flow of water from it to the other is practically infinite; but an effort to flow exists which is proportional to the height of the column of water and takes the form of a pressure on the bottom of the tank, and if we interpose a relatively bad conductor of the water in the form of a very small pipe or tube between the tanks, there will be a correspondingly weak or feeble flow of water from the higher to the lower tank. If we increase the size or bore of the pipe, the conducting power will be increased proportionally, and a corresponding increase in the volume of the water (or in the strength of the current) flowing will be observed. Pursuing this to its finality, if the bottom of the upper tank is removed instantaneously there will result an equally instantaneous fall of the whole of the water in the tank. Such a state of things can easily be traced between two bodies charged to different electrial potentials or pressures and connected in turn by various substances whose conducting powers range from the almost infinitely great to the almost infinitely small; or, in other words, by varying the amount of resistance, which is here shown to be the

converse or reciprocal of conductivity, we can, in a corresponding degree, vary the strength of the current.

To summarise our observations on the question of resistance, we may say that if we electrify two bodies, connected only by the air, to different potentials, we subject the intervening air to a species of stress. If we very considerably increase the potential, the air being no longer able to sustain the stress, a discharge or an electric flow ensues, in just the same way that we could force the bottom out of a tank of water and empty it by sufficiently increasing the pressure. A similar result can be achieved, without increasing the potential difference, by reducing the distance between the electrified bodies, or by bridging over the air-space with a piece of wire or other good conductor. In either case the ability to sustain the stress is reduced, and we call this ability to sustain the electrical stress, resistance. The more resistance we insert between the electrified points or bodies, the more do we thereby reduce or prevent the flow of electricity from one to the other.

CHAPTER II

PRACTICAL UNITS—OHM'S LAW—FUNDAMENTAL UNITS

In dealing in the previous chapter with the general attributes of electricity, the only degree of comparison arrived at was to say that one electrification, resistance, or current was greater or less than another. It is, however, essential that more precision in comparing or measuring forces and their properties and effects should be obtained. Measurement is, in fact, the most important branch of electrical science, as, indeed, it is of every other physical science.

Instead of simply saying that one lump of iron is heavier or weightier than another, it is usual to say by how much they differ, Thus one lump may have a mass of twenty pounds, and another a mass of thirty pounds. The latter is therefore ten pounds heavier than the former. We have here introduced a unit of measurement, viz. the pound or unit of mass. Similarly the inch or foot may be used as a unit of length, the second as a unit of time, the pint as a unit of capacity, the sovereign as a unit of coinage, and so on. These units are all such as everybody can readily appreciate. They are so frequently employed that no mental effort is required to understand what is meant when any one of them is mentioned.

In dealing with electricity, the first thing we wish to measure is the amount of the electrical difference between two bodies which causes an electrical stress, and which may result in a current of electricity. But we are confronted with two difficulties. The first is that by none of the everyday units—by no unit employed for any other purpose—are we able to indicate exactly the electric potential of a body. Moreover, electricity being not matter itself, but only a manifestation of energy which induces or causes

a certain condition of matter, it is impossible to measure it directly. We can only measure it by its effect upon material substances. In the next place, inasmuch as it is impossible to obtain or even to conceive of a body altogether devoid of electrification (although such electrification is not always perceptible), it is impossible to fix on an absolute zero potential, and to measure potentials from that point. In just the same way it is impracticable to have a zero level, some arbitrary point, such as the sea-level at high tide, having to be employed if we wish to measure the relative height of two or more points. It is, consequently, necessary to look elsewhere for a starting point, and to fix on a convenient arbitrary potential zero. We take as a convenient zero the potential of the earth's surface, and consider that bodies which are said to be positively electrified are at a higher potential than the earth, while negatively electrified bodies are at a lower potential. Positive and negative potentials may therefore be said to correspond to height and depth in their relation to the sea-level. Inasmuch, however, as we are unable to detect any potential at all unless we take two points or bodies whose potentials are different, the direct measurement of potential itself again presents difficulties. On the other hand, when we are called upon to measure the potentials of two bodies, what we really desire to know is the difference between those potentials; or, if we call the potential of one body P, and that of the other p, we want to know the value of $P-p$; for after all, it is this *difference* of potential that determines the flow of electricity. This difference of potential, which, when the conditions are favourable, is competent to develop and maintain a current of electricity, is known as electro-motive force, a term which is frequently contracted into the initials E.M.F., or shorter still, into E. only. It is this electro-motive force, then, that we desire to measure, and the practical unit by which it is measured is known as the *volt*. We will, for the present, rest satisfied with the simple statement that the volt is approximately equal to, although actually a fraction less than, the electro-motive force of a single Daniell cell. (See Chapter III.)

Reference was made in the previous chapter to 'resistance,' and it was described as the converse of conductivity, which again we described as the ability of a body to transmit a current of

electricity. It is easy to show that resistance may be expressed as a ratio—the ratio of electro-motive force to current—and many authorities insist that it should always be regarded thus. It may also be expressed as a 'velocity,' or the ratio of length to time; but we prefer to deal with it as it appeals to practical electricians, viz. as an attribute of matter, varying with different substances, and in virtue of which such matter opposes or resists the passage of electricity, whence the current has to do 'work' or expend 'energy' in effecting the passage. The law of the conservation of energy teaches us that energy is indestructible, and it follows, therefore, that if energy has to be expended in impelling a flow of electricity against a greater or less amount of resistance, the equivalent of that energy must be developed in some other form. This other form is usually heat; or, in other words, when a body opposes a certain amount of resistance to the passage of electricity, heat is produced, the actual amount of heat being an equivalent of the energy expended in overcoming the resistance and varying, therefore, directly as that resistance. Consequently, if we have two conductors, the resistance of one of which is twice that of the other, and if we send currents of equal strength through both wires, twice as much heat will be developed in the conductor of the higher resistance as will be developed in that offering the lower resistance. We shall have occasion to deal with this subject more fully in a future chapter, but we may add here that if we wish to perform work at any point by means of an electric current conducted by a wire to that point, we must keep the resistance of that wire down to the lowest practicable limit, because every fraction of the energy frittered away in heating the conductor means so much less energy available for the particular work which we wish the current to perform at the far end of the conductor. It is apparent, then, that we require a unit by which we shall be able to compare the resistances of various substances, and the unit selected is called the *ohm*. For use as a practical unit for measurement and comparison this standard takes the form of a specially constructed coil of wire; but for the ultimate standard of reference a thread or column of mercury is chosen, because it is possible to more precisely define and to reproduce those conditions, such as the dimensions and density, which determine the actual resistance

of such a thread or column. The standard *ohm* is therefore defined as the resistance offered by a thread or column of pure distilled mercury 106·3 centimetres in length, weighing 14·4521 grammes at 0° C. and of uniform sectional area. The sectional area of such a column is one square millimetre. (The metre is equal to 39·37 inches, the centimetre to 0·3937 inch, and the millimetre 0·03937 inch. The length of the column of mercury is 41·85 inches, and its weight is 0·509 ounce avoirdupois.)

It is convenient to remember that one mile of copper wire a quarter of an inch in diameter offers a resistance of slightly less than ohe ohm. A milllionth part of an ohm is called a microhm, and one million ohms a megohm. The ohm is frequently indicated by the symbol ω, and the megohm by the symbol Ω; thus 15 ω means 15 ohms, and 4 Ω represents 4 megohms, or 4 million ohms.

A quantity of apparatus, however, constructed on the basis of the so-called B.A. unit is still in use. This unit was determined in 1863 by a committee appointed for the purpose by the British Association, and the standard ohm as defined above is the latest correction of this unit. One standard ohm is equal to 1·013 B.A. unit; and one B.A. unit is equal to 0·9866 standard ohm.

The student will frequently come across the expression 'specific resistance,' and it is a most important term. The specific resistance of any substance may be defined as the resistance which that substance offers in consequence of its nature and composition, irrespective of its dimensions and temperature. Obviously the best way to compare the specific resistances of various substances is to state the resistance offered by specimens of those substances having exactly the same dimensions, and being all at the same temperature.

It is a matter ot great convenience that different bodies vary in their specific resistances, for there are times when we want the lowest possible resistance, while at other times we require a large measure of resistance, more particularly when we desire to prevent an electric discharge, to impede the flow of an electric current, or to prevent electricity leaking from one body to another. Silver, because it is the best conductor, is the most convenient substance

to take as a standard of reference. Appended is a table, based upon the experiments of Dr. Matthiessen, which shows the specific and also the relative resistance of a number of metals frequently met with; and as the variation of the temperature of a body alters its electrical resistance, all the tests have been taken at a common temperature, viz. that of freezing-point, or the necessary corrections have been made to correspond to that temperature.

TABLE SHOWING RESISTANCES OF CHEMICALLY PURE METALS AND ALLOYS AT 0° C. IN STANDARD OHMS

Name of Metal	Relative Resistance	Resistance of a wire 1 foot long, $\frac{1}{1000}$ of an inch in diameter	Resistance of a wire 1 metre long, 1 millimetre in diameter	Specific resistance, cubic centimetre microhms
Silver, annealed	1·000	9·0283	0·01911	1·5006
Copper, annealed	1·063	9·5877	0·02029	1·5943
Silver, hard drawn	1·086	9·8028	0·02074	1·6298
Copper, hard drawn	1·086	9·8068	0·02075	1·6298
Gold, annealed	1·369	12·3522	0·02614	2·0531
Gold, hard drawn	1·393	12·5692	0·0266	2·0896
Aluminium, annealed	1·935	17·4825	0·037	2·9055
Zinc, pressed	3·741	33·7614	0·07145	5·6127
Platinum, annealed	6·022	54·3517	0·11503	9·0352
Iron, annealed	6·460	58·308	0·12342	9·6933
Lead, pressed	13·05	117·7901	0·24921	19·584
German silver, hard or annealed	13·92	125·6139	0·26588	20·8863
Platinum-silver alloy ($\frac{1}{3}$ platinum, $\frac{2}{3}$ silver), hard or annealed	16·21	146·3621	0·30979	24·3295
Mercury	62·73	570·8467	1·20828	98·4034

The figures given in the right-hand column represent the specific resistance of the various substances; they state in millionths of an ohm the resistance offered between two opposite faces of a cubic centimetre of each particular metal or alloy.

An alloy of copper, nickel, and zinc (the usual constituents of German silver), combined with 1 or 2 per cent. of tungsten, and known as platinoid, is largely used in electrical work. It is found that the addition of tungsten imparts greater density to alloys and reduces any tendency to oxidation. When polished the alloy is scarcely distinguishable in appearance from silver. A cubic centimetre offers between opposite faces a resistance ranging from about 30 to 36 microhms, so that its resistance is about one and

a half times that of German silver. As, however, alloys always vary more or less in their composition, a definite resistance cannot safely be assigned to any commercial variety, and calculations concerning them can only be accepted as actually true of the particular samples tested. Platinoid, when drawn hard, is, like copper, softened by heating and sudden cooling.

The admixture of even a minute proportion of foreign matter very considerably reduces the conductivity, or increases the resistance, of a metal. A very remarkable effect is observed when an alloy of two or more metals is tested, for the specific resistance of the alloy will usually be found to be higher than that of either of its constituents. Purity in the case of simple metals and absolute uniformity in the constitution of alloys, such as German silver, are, therefore, pre-eminently essential if the highest conductivity or if a certain specific resistance is desired. As a matter of fact, there are to be found samples of commercial copper which offer as much as six times the resistance of the chemically pure material, and which are, therefore, little better than iron as conductors.

Or, again, if the relative conductivity of pure copper be taken at 100, then that of copper mixed with 1·6 per cent. in volume of silver will be only 65; while the conductivity of silver mixed with 1·2 per cent. in volume of gold will be 59 when that of pure silver is taken as 100.

A highly interesting phenomenon is the wonderful effect which a variation in temperature produces upon the resistance of the various substances through which a current may flow. The effect would be less surprising were it general, or were it consistently uniform in all bodies; but the great feature to be observed is that while in the case of metals the resistance of a conductor invariably increases with an exaltation in temperature, the non-metals all show a decrease in resistance under similar circumstances. It is also a remarkable fact that in the case of metals the variation is much less in alloys than in pure metals. These results are fraught with the greatest importance, as they limit considerably the number of substances available for many classes of electrical apparatus. For example, wires which are to be employed as standards for comparing or measuring resistances should have as nearly as possible the same value at all temperatures, and the alloy platinoid

is of exceptional value because of the very slight change in its resistance consequent upon even a considerable variation in temperature. The accompanying table, showing the percentage-variation in the resistance of various bodies between the temperature of freezing water and that of boiling water should prove eminently interesting. It is certainly useful and important.

Name of Metal	Conducting power at 0° C. Silver = 100	Percentage fall of conducting power between 0° and 100° C.
Pure iron	16·81	39·2
Pure thallium	9·16	31·4
Other pure metals in a solid state	—	29·3
Gold with 15 p.c. iron	2·76	27·9
Proof gold	72·55	26·4
Standard silver	80·63	23·2
Gunmetal	27·08	18·3
Copper with 25 p.c. platinum	22·08	11·5
Silver with 5 p.c. platinum	31·64	11·3
Silver with 9·8 p.c. platinum	18·04	7·1
Copper with 9·7 p.c. tin	12·19	6·6
Gold-silver alloy	15·03	6·5
Platinum with 33·4 p.c. iridium	4·54	5·9
German silver	7·80	4·4
Gold with 4·7 p.c. iron	2·37	3·8
Silver with 25 p.c. palladium	8·52	3·4
Silver with 33·4 p.c. platinum	6·70	3·1
Platinoid	—	2·09

As may have been gathered from what has already been said, when we increase the length of a conductor we invariably increase its resistance. This follows as a matter of course from the fact that if we urge a certain current through a wire of increased length, we give it more work to do, necessitating, consequently, a greater expenditure of energy, in precisely the same way that a railway engine would consume more coal in taking a train a distance of 200 miles than would be required to cover half that distance. The resistance of a conductor of uniform material and thickness or cross-section varies directly as its length—that is to say, if we vary the length of the conductor we vary its resistance at exactly the same rate. If, for example, a mile of wire of a certain gauge offers a resistance of 10 ohms, two miles of the same wire would offer 20 ohms.

The effect of increasing the size or sectional area of a conductor is to increase its conductivity and, consequently, to diminish its resistance, in exactly the same way that increasing the diameter of a pipe increases the amount of gas or water that can be passed through it. The resistance of a conductor varies inversely as its sectional area. That is, if we have two conductors such as two specimens of copper wire equal in length and drawn from the same bar, the resistance which the wires will offer depends upon the size of the wires, or on the area of the ends exposed on cleanly cutting them at right angles to their length—that is to say, upon the amount of metal through which the current can flow. Most wires are round, so that the section is a circle, and it becomes necessary to understand the method of comparing the areas of circles. The area of a circle varies as the square of its diameter; for example, if we have two circles, one having a diameter of one-tenth of an inch and the other of two-tenths of an inch, their areas or the spaces they enclose will not be in the proportion 1 : 2, but as the squares of those figures, viz. 1 : 4, so that one wire which is twice the diameter of another, other things being the same, offers only one-quarter of the resistance offered by the thinner wire. While if we treble the diameter of the wire, or make it three-tenths of an inch, the resistance will be only one-ninth of that of the thinnest wire. As a matter of fact, the thickest of these three wires will weigh exactly nine times as much as the thinnest, there being nine times as much metal in it. We may therefore state our law in other words by saying that the resistance of circular wires uniform in all particulars excepting thickness varies inversely as their weight. Thus, if a mile of copper wire weighs 100 lb., and has a resistance of 9 ohms, and an equal length of similar copper wire weighs 150 lb., the resistance of the latter will be 6 ohms. Again, the specific resistances of iron and copper are approximately as 6 to 1. If, now, a mile of iron wire, 0·240 of an inch in diameter, has a resistance of 5 ohms, and it is thought for certain reasons desirable to substitute a mile of copper wire having the same resistance, we should have to use wire weighing one-sixth the weight of, or whose sectional area would be one-sixth of that of, a copper wire approximately 0·240 of an inch in diameter, because the resistance of a mile of the latter would be

only five-sixths of an ohm. The required thickness could be ascertained by rule of three, for if x stands for the required diameter,

$$6 : 1 : : (0{\cdot}240)^2 : x^2,$$

from which we find $x^2 = 0{\cdot}0096$. Therefore x, or the required diameter, is equal to the square root of $0{\cdot}0096$ or $0{\cdot}098$ of an inch nearly.

A conductor offers to the passage of electricity, at a given temperature, a constant resistance which is altogether independent either of the electro-motive force or of the strength of the current. That is to say, a wire which offers 10 ohms resistance to the passage of a feeble current offers precisely the same resistance to a powerful current, except in so far as an increase in the strength of the current involves a corresponding increase in the temperature of the wire, and this increased temperature causes a proportionately increased resistance, as has already been pointed out.

We come now to the consideration of the laws which determine the strength of a current and of the relationship subsisting between strength and the other attributes of an electric current. The real relationship can, perhaps, be best understood by the aid of a simile. Let us suppose two tanks, one very high up, say a hundred feet above the ground, the other raised only a few feet. Let both tanks contain the same quantity of water, and let both of them be supplied with pipes, the one for the upper tank being, however, very much smaller in diameter than that for the lower. On turning the taps the water from the upper tank will issue forth with much greater force than that from the lower tank, although the quantity or rate of flow from the lower tank may considerably exceed that from the upper tank. In other words, the pressure in the long small pipe is much greater than in the short but large one, while the quantity of water delivered by the former is considerably less than that delivered by the latter. Pressure in the case of a column of water corresponds with the electro-motive force of a battery, while the volume or quantity of water flowing through the pipe corresponds to current strength. But to pursue the analogy still further, if the upper tank be raised sufficiently high, the greater pressure so obtained will augment the velocity of the water, and the two tanks may then be emptied in the same time.

There are two things, then, that govern the quantity of water delivered or the rate of delivery, viz. the pressure, and the size of the pipe: the latter corresponds in electrical considerations with the size of the conductor, and consequently with the resistance.

By current strength is meant, therefore, the rate of flow of electricity, and it is measured by the quantity of electricity passing any point in a circuit during a given time. It corresponds to the rate of delivery of gas or water by a pipe. In a simple circuit it depends upon two things— the electro-motive force of the generator or battery, and the resistance of the whole circuit, comprising the wire and apparatus as well as the battery itself. The practical unit of current strength or rate of delivery is called the *ampere*, and it is that strength of current which is developed in a circuit of one ohm resistance by an electro-motive force of one volt. If this current be maintained for one second, one unit of electrical *quantity* is delivered, and this unit is called the *coulomb*. If a current of half an ampere flows for two seconds, the quantity of electricity delivered is again one coulomb. So also is it if a current of two amperes flows for half a second; so that in every case the rate of flow, or current strength in amperes, multiplied by the time in seconds, gives us the total quantity of electricity or the number of coulombs. Thus, if Q represents the quantity of electricity in coulombs, C the current strength in amperes, and t the time in seconds,

$$Q = C \times t.$$

As the quantity of electricity delivered is rarely required to be known, but rather the rate of delivery or flowing, we will deal more fully with the method of ascertaining this rate. In order that this matter may be more readily understood, we will at once proceed to the discussion of 'Ohm's Law,' which declares that *the current strength varies directly as the electro-motive force and inversely as the resistance.* This law may be represented by the simple equation—

$$\frac{\text{Electro-motive force}}{\text{Resistance}} = \text{Current strength},$$

or,

$$\frac{E}{R} = C.$$

As an example of the relation which the units bear to each other, we may take the simple case of a battery-cell having an electro-motive force of one volt and sending a current through a circuit whose total resistance is one ohm. The current strength will then be one ampere, thus :—

$$\frac{1 \text{ volt}}{1 \text{ ohm}} = 1 \text{ ampere},$$

and if this current is maintained for one second, one coulomb of electricity will have passed. By doubling the resistance we get—

$$\frac{1 \text{ volt}}{2 \text{ ohms}} = 0{\cdot}5 \text{ ampere}.$$

Similarly, by doubling the electro-motive force we get, with unit resistance,

$$\frac{2 \text{ volts}}{1 \text{ ohm}} = 2 \text{ amperes}.$$

A little reflection will make evident the subsidiary law that *the current strength is the same in all parts of the circuit*, and does not in any sense vary in different parts of the same circuit. The current strength can easily be supposed to be uniform in a uniform conductor; but if we make up a circuit with wires of different degrees of conductivity, or if we interpose any liquid conductor, the same law holds good, just as would be the case if we were to urge a current of water through a pipe of variable diameter. It is manifest that if a gallon of water enters the pipe in a certain time, the same volume must pass out in the same time (supposing the pipe to have been already full), and the same volume must pass every point in the pipe in the same interval of time, although in the thinner or smaller portions of the pipe the water travels faster and generates a little more heat by friction with the sides of the pipe than in the larger sections of it. This latter analogy also holds good in a measure with regard to electricity, for in the thinner wire or poorer conductor more heat will be developed by the current than in the thicker or better conductor. It is this fact that makes electric lighting by incandescent lamps possible. It is doubtful whether in the whole range or history of electrical science a law has ever been enunciated so full of truth and of such

immense importance as that discovered by George Simon Ohm, and we shall find frequent need to refer to it in the succeeding chapters.

For the benefit of those who do not understand the full meaning of a simple equation we may say that if

$$\frac{E}{R} = C, \text{ then, } \frac{E}{C} = R, \text{ and}$$

$$E = RC \text{ (or } R \times C).$$

So that if of these three quantities we know any two, we can always readily calculate the third. Thus, with a current of 2 amperes and an electro-motive force of 10 volts, the resistance will be

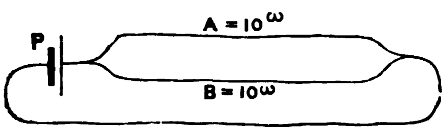
$$\frac{10}{2} = 5 \text{ ohms.}$$

Similarly, if a current of 5 amperes flows through a resistance of 10 ohms, the electro-motive force capable of maintaining this current will be

$$10 \times 5 = 50 \text{ volts.}$$

When two or more channels or paths are open to a current of electricity, the current divides between them, just as water or gas in a pipe will divide into any number of branch pipes. If in the case of electrical conductors there are two wires (A and B, fig. 5), between which the current can divide, and if the resistances of the two wires are equal, the current will divide equally

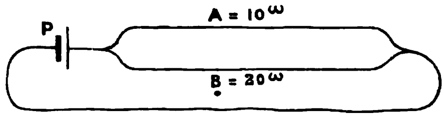
FIG. 5



between them ; thus, if a current of two amperes flows from the battery P, one ampere will go through each wire, the two currents re-uniting at the junction and returning to the battery by the common wire. When the resistances are not equal, the current will divide directly as the conductivities or inversely as the resistances : thus, if the resistance of one wire (A, fig. 6) is 10 ohms, and of

another (B) is 20 ohms, and a current of three amperes divides between them, two amperes will go through the wire A of 10 ohms and one ampere through the wire B of 20 ohms.

FIG. 6



When two or more wires are thus joined together so that the current divides between them, they are said to be joined up in 'parallel'; but when the end of one is joined to the end of another so that the whole current goes through both wires in succession, the wires are said to be joined up in 'series.'

The law for two parallel conductors holds equally good for a larger number. Thus, if there are 10 wires of uniform resistance and a current of 10 amperes divides between them, it will do so equally, so that one ampere will flow through each wire. When the resistances vary, then the current flowing through each wire will vary also, but in the inverse ratio to the resistances.

When, however, a second wire is joined up in parallel with a wire already forming part of a circuit, a serious alteration is made in the condition of the circuit, for the total amount of current that is produced, whether it be from a primary battery, a dynamo-electric machine, or any other source of electrical energy, will be increased. This increase follows from the fact that when wires are joined up in parallel their united or, technically speaking, their joint resistance is less than that of any one of the wires taken separately. The meaning of this will be more readily apparent if a wire is regarded as a conductor rather than as a source of resistance. Thus, if two equal wires lie side by side and the current is allowed to flow through them, the conducting power of the double wire will be twice that of either wire taken separately, in precisely the same way as a water or gas pipe two square inches in section will transmit twice as much as a similar pipe only one square inch in section. If, therefore, the conductivity of the two wires in parallel is twice that of one of them, their united or joint resistance will be only half that of one of them. Thus, if two wires, each of 100

ohms resistance, are joined in parallel to a battery, their joint resistance will be 50 ohms. Similarly, if ten wires, each of 100 ohms resistance, are joined in parallel, they will offer a joint resistance of 10 ohms. We may, therefore, say that if any number of wires (n) of uniform resistance (R) are joined in parallel, or 'multiple arc,' as the arrangement is sometimes called, then their joint resistance $= \frac{R}{n}$. Suppose, now, that our battery has an electro-motive force of 100 volts, and that its internal resistance is negligibly low; with one wire of 100 ohms joined on we get—

$$\frac{100 \text{ volts}}{100 \text{ ohms}} = 1 \text{ ampere.}$$

With two such wires we get—

$$\frac{100 \text{ volts}}{\frac{100}{2} \text{ ohms}} = \frac{100}{50} = 2 \text{ amperes.}$$

This current divides equally between the two wires, one ampere going through each.

With ten wires we get—

$$\frac{100 \text{ volts}}{\frac{100}{10} \text{ ohms}} = \frac{100}{10} = 10 \text{ amperes.}$$

Whence one ampere will still go through each wire, so that the strength of the current increases in precisely the same proportion as the number of wires. As, however, the current developed by the battery has to pass through it as well as through the wire, the resistance of the battery itself forms part of the resistance of the circuit. If, therefore, the internal resistance of the battery is proportionally high enough to necessitate its being taken into account, the reduction of the external resistance will not produce so marked an effect. With a battery resistance of 100 ohms and a single wire of a like resistance we get—

$$\frac{100}{100 + 100} = \frac{100}{200} = 0{\cdot}5 \text{ ampere,}$$

and when two wires are joined in parallel we get—

$$\frac{100}{100 + \frac{100}{2}} = \frac{100}{150} = 0{\cdot}66 \text{ ampere.}$$

With ten wires we get—

$$\frac{100}{100 + \frac{100}{10}} = \frac{100}{110} = 0{\cdot}90 \text{ ampere.}$$

Thus with two wires in parallel a current of 0·33 ampere would flow through each wire, while with ten wires the current strength in each wire would be only 0·09 ampere.

When the parallel circuits are of different resistances the calculation of their joint resistance involves a little more trouble. We have already pointed out that resistance is the converse of conductivity, or conductance as it is generally called, so that if the resistance of a conductor is symbolized by R, its conductance would be $\frac{1}{R}$. If R is unity, then we have one *mho* or unit of conductance, that is to say $\frac{1}{1 \text{ ohm}} = 1$ mho. This method of calculating is sometimes convenient. Let us suppose two wires to be joined in parallel, their individual resistances being R_1 and R_2 respectively, then their conductances will be $\frac{1}{R_1}$ and $\frac{1}{R_2}$, and their united conductance will be $\frac{1}{R_1} + \frac{1}{R_2}$ which is equal to $\frac{R_1 + R_2}{R_1 R_2}$. If $R_1 = 500$ ohms and $R_2 = 1000$ ohms, the conductance will be $\frac{1}{500} + \frac{1}{1000}$ or $\frac{500 + 1000}{500 \times 1000} = 0{\cdot}003$ mho.

But the converse of $\frac{R_1 + R_2}{R_1 R_2}$ is $\frac{R_1 R_2}{R_1 + R_2}$ and this will represent the joint resistance, or

$$\frac{500 \times 1000}{500 + 1000} = \frac{500{,}000}{1500} = 333{\cdot}3 \text{ ohms.}$$

Briefly put, it may be said that the joint resistance of any two conductors is equal to the product of those resistances, divided by their sum.

Similarly, with three (or more) wires of different resistances, their united conductance would be—

$$\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} = \frac{R_1 R_2 + R_2 R_3 + R_1 R_3}{R_1 R_2 R_3} \text{ mhos,}$$

whence the joint resistance will be

$$\frac{R_1 R_2 R_3}{R_1 R_2 + R_2 R_3 + R_1 R_3} \text{ ohms.}$$

If R_1, R_2, and R_3 are 500, 1000, and 2000 ohms respectively, their joint resistance will therefore be

$$\frac{500 \times 1000 \times 2000}{(500 \times 1000) + (1000 \times 2000) + (500 \times 2000)}$$

$$= \frac{1,000,000,000}{5,500,000} = 285 \cdot 7 \text{ ohms.}$$

It should be obvious that the united conductance of any number of parallel conductors must be greater than the conductance of any one of them, or conversely the joint resistance of any number of parallel conductors must be less than the resistance of the best conductor.

In the process of electrical testing it is frequently found to be necessary to employ wires of various resistances, either as standards, for comparison, or simply for the purpose of inserting in a circuit to vary the strength of the current therein. The wires are usually coiled up or wound on bobbins, so as to occupy little space, and they are then placed in a convenient case or box. Such a set of coils is known as a resistance-box, or rheostat. But if the coils are to be made of any real value as standards or for measuring purposes, great care must be exercised not only in ascertaining their exact resistance, but also in selecting the materials of which they are made, so as to avoid deterioration or change of any kind. The wire must be completely covered throughout by some good insulating substance, to prevent contact between adjacent convolu-

tions, and the material used for this purpose must be able to withstand without change the highest temperature to which it is likely to be subjected; and it must also be incapable of producing any injurious action on the wire. The best insulating material for such resistance coils is silk thread, which is wound spirally over the wire in one or two layers. The metal employed for the conductor must be free from any liability to oxidation; and another important matter for consideration is the amount of its variation in resistance with a given change of temperature.

In very important work it is necessary to know the temperature at which a coil was originally measured, and either to bring it to that same temperature during the experiment, or else to make a correction in the result. But either course is somewhat tedious, and in ordinary cases impracticable. In practice the coils are measured at the temperature near which it is probable they will generally be used, say 15° C. (59° F.), and the error lessened by employing a metal whose percentage of resistance variation with change of temperature is very low.

In addition to changing with any alteration in the temperature of the atmosphere, the wire is more or less heated by the passage of the current itself, so that the resistance of the wire may easily alter during even a brief or rapidly performed test or experiment. An examination of the table given on page 20 shows the variation of a platinum-silver alloy and also that of platinoid to be very small, and these alloys are therefore very extensively employed in high-class apparatus.

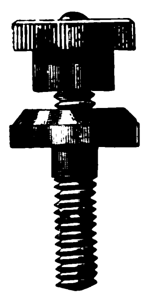
For coils of high resistance it is necessary to choose a metal whose specific resistance is high; otherwise the length of wire would sometimes be inconveniently great. For low resistances, however, this is not so important; in fact, if a metal of high specific resistance is then used, the wire must be comparatively thick, otherwise it would be so short that very great difficulty would be experienced in making the coils of exactly the right resistance, because a considerable difference would be caused by a small error in the length of the wire. In all cases, however, there is the great advantage in the use of a thick wire that a given amount of heat raises its temperature to a less extent than it would a thinner wire.

Copper is unsuitable for ordinary resistance coils on account of its great variation in resistance under a variation of temperature; and, as its specific resistance is low, it would be necessary to employ either a very long or a very fine wire to make a coil of high resistance. Taking into consideration cost, durability, high specific resistance, and low temperature error, German silver is undoubtedly the most useful material for general purposes, and it is consequently used more frequently than anything else.

A single resistance coil—such, for example, as a standard coil, or one designed for some other special purpose—is, after having been carefully wound on an ebonite or boxwood bobbin, usually mounted in a case or box furnished with an ebonite cover. Two brass blocks or plates, to which the ends of the wire are soldered, are screwed on to the under side of this cover. Connection with the external circuit is made by means of terminals fixed on the top of the case, and connected electrically with the plates underneath. The form of terminal employed is a matter of more importance than it is usually considered to be, for the contact surfaces at the junction of two conductors always offer some resistance, and if these surfaces are oxidised or dirty, or if the contact is not firm, this resistance will probably be considerable. It is for this reason that the form of terminal or binding screw shown in fig. 7 is open to serious objection, the contact being as a rule uncertain. Such terminals, in which dependence for good contact has really to be made upon the end of a screw (frequently pointed as if to accentuate the evil), should be avoided, at least for small wires or such as can be readily bent with the fingers. A much better and more reliable terminal is that shown in fig. 8, where the wire is clamped between a fixed base and a screw nut. In tightening the nut a rubbing effect is produced, which assists in removing any superficial dirt either on

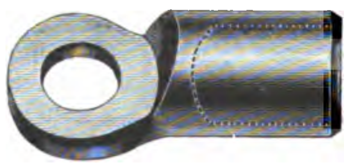
FIG. 7

FIG. 8



the wire or on the terminal, and so tends to insure good and reliable contact. When using this terminal the wire should be bent round the screwed stem, and not simply gripped upon one side of it, otherwise there will, in tightening up, be a risk of bending the stem. The end of the wire should also be bent round the back of the stem from left to right, that is in the direction in which the nut is turned, so that the nut in turning shall draw the wire in towards the stem If the wire is bent in the opposite direction it will frequently happen that the wire is squeezed out of the terminal. With the large wires used on electric lighting and power circuits it is inconvenient, and sometimes impracticable, to bend the conductor. In that case the first-mentioned type of terminal (fig. 7), or a modification of it, is occasionally resorted to, but the best plan in such cases is to solder a brass thimble (fig. 9) on to the end of the conductor, the free end being provided with a flat lug or shoulder through which a hole has been drilled large enough to allow it to be slipped over the stem of a terminal. A good electric contact can then be ensured by screwing the nut down firmly, for which purpose the nut should be square or hexagonal, so that it can be tightened by means of a spanner.

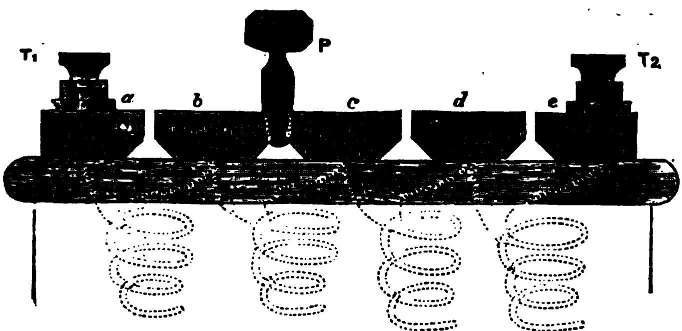
FIG. 9



As it more generally happens that a number of coils are required to be so put together that the resistance to be introduced into any particular circuit can be varied at will from zero to the maximum, special devices have to be employed to obtain this result with the smallest possible waste of time. Fig. 10 shows the best method of casing a number of coils of various resistances; all the coils are joined in series, and the junction of each pair is soldered to the bottom of a brass block, or, better still, to a pin projecting from the under side of the block. Care is taken in winding to insure the absence of contact or leakage between one portion of the wire and another, and this is particularly desirable in the method of winding shown in the figure (and referred to on page 34), as with such winding there is the maximum potential

difference between adjacent turns of wire at the outer end of every coil, and therefore the greatest risk of 'short-circuiting' or the leakage of the current from one wire to the other. The bobbins are fixed to the under side of the ebonite top of the case, the wires being connected to the brass blocks *a*, *b*, *c*, *d*, *e*, which are firmly fixed to the upper side of the ebonite, the adjacent ends of the various blocks being turned out to receive a slightly tapered or conical brass plug. The end blocks are fitted with terminal screws, T_1 and T_2, to which any external wires can be connected. Now, if a wire leading from the copper pole of a battery is joined to the terminal T_1, and another from the zinc pole to T_2, a current will flow through the coils in the resistance-box, starting

FIG. 10



from the left-hand block, *a*, and passing through the resistance coil No. 1 to the second block, *b*. Here it has two paths open to it: one through the coil No. 2, of comparatively high resistance, and the other through the brass plug P, which has, practically, no resistance at all. All the current will therefore pass by the latter path, and none through the coil, which under these circumstances is said to be 'short-circuited' by the plug P. The current must pass through the coils 3 and 4 before it reaches the terminal T_2. If we suppose coil No. 1 to offer a resistance of 100 ohms, No. 2 of 200 ohms, No. 3 of 300 ohms, and No. 4 of 400 ohms, the total resistance interposed in the circuit by means of the resistance box with a plug in the position illustrated will be

$100+300+400=800$ ohms, and the range of the box will be from zero to 1,000 ohms in steps of 100 ohms.

The brass plug, which should be furnished with an ebonite cap or top, must be carefully tapered to fit the hole *exactly*. Should there be the slightest shake, or should there be any dirt or grit on the blocks or on the plug itself, the contact will be uncertain and the resistance variable. When properly made, the plug, on being inserted with a little pressure and a slight twist—say to the right—should fit so thoroughly that on raising it the resistance-box should be lifted with it. The pressure applied should not be excessive, otherwise there will be some risk of distorting the cover of the box or of displacing the blocks. The plug should not be made so long that it can butt against the ebonite at the bottom of the hole, and should the plug in course of time wear so much that it does touch the bottom, the end should be filed off. To remove the plug it should be necessary to first loosen it by giving a slight twist, say to the left. There should be as many plugs as there are coils. The lower and the two vertical edges or corners of the blocks should be cut away, to give a larger ebonite insulating surface between the blocks and to allow this surface to be kept clean. This arrangement is necessary in order to prevent, as far as possible, any leakage being caused by the accumulation of dust and dirt.

Resistance coils fitted in this way can easily be put in or taken out of the circuit by withdrawing or inserting plugs between the brass blocks to which the ends of the various coils are connected. It is hardly necessary to remark that the surfaces of contact should not be lacquered, but should be kept bright and clean. The slight twisting recommended above in inserting a plug serves the further useful purpose of keeping the contact surfaces clean.

Resistance coils are frequently used in conjunction with and in the immediate vicinity of delicate measuring apparatus in which a sensitive magnetised needle is employed. If, in such cases, the coils are wound continuously on the bobbin, or like cotton on a reel, an 'electro-magnetic field' will be set up immediately a current is sent through the coils, which may be sufficiently strong to impart motion to the needle of the measuring instrument. If the instrument is being employed to measure either the current

passing through the resistance coils or any effect of that current, serious errors may be introduced by the direct effect of the coils upon the needle. Again, as we shall see later on, it is impossible to suddenly start or stop a current in such a coil, because work is done and time occupied in establishing, and again in disestablishing, the electro-magnetic field. These are serious defects, and it is fortunate, therefore, that the remedy is simple.

To obviate the difficulty it is only necessary that the wire should be wound 'double'—that is to say, the required length should be measured off and then doubled in the middle, the two halves being wound on together. The meaning of this will perhaps be more apparent on referring to the illustration (fig. 10). The double winding is more easily managed, especially with long

FIG. 11

coils, by winding the two halves off two separate spools or bobbins and soldering the inner ends together. In either case the two extremities of each coil are brought out together. We have thus two similar helices carrying currents equal in strength but opposite in direction, and the consequence is that the disturbing effect which would be produced by one helix is exactly counteracted or neutralised by the opposite effect which would be due to the other.

When the coils to be enclosed in a box are numerous, it is inconvenient to place them in one long row, and thus make a long narrow box. It is preferable to arrange them in two, three, or more parallel rows, connecting these rows together by brass blocks and plugs, as indicated in fig. 11. The centre of each block may also be provided with a tapered hole, of the same size as those

between the blocks, in order that the plugs may be placed in them when not in use for short-circuiting the coils. It is most important that all the holes and all the plugs should be of exactly the same dimensions, so that the plugs may be interchangeable, or that any one plug may be used for any of the holes. Failing this, considerable inconvenience and risk of error would speedily ensue, for then there would be a particular plug for each hole, and very great difficulty would be experienced in using them and keeping them in their proper places.

Another very useful form of resistance-box or rheostat is shown in fig. 12. The coils are placed inside a round brass case

FIG. 12

or box provided with an ebonite top and mounted on a mahogany base. Ten coils, each of 40 ohms resistance, are connected to eleven rounded steel points projecting through the ebonite top of the instrument. Ten other coils, each of 400 ohms resistance, are connected to the steel points on the other half of the top side of the ebonite. Three more coils are connected to the brass blocks fixed on the wooden base of the instrument; when not required the last-mentioned coils are short-circuited by the usual brass plugs. Supposing the current to enter by the right-hand terminal, it will pass to the nearest brass block, then

through the coils of 4,000, 20, and 10 ohms (or through such plugs as may be inserted between the respective blocks), to the brass block nearest to the left-hand terminal. It then passes by a piece of insulated wire under or in the base of the instrument to the zero stud on the right-hand side, whence it will pass through the 40-ohm coils until it reaches the steel spring carried by the front brass arm, which is movable over these coils and studs. Passing along this arm, which is metallic throughout, it will enter the other movable arm, and thence pass to the 400-ohm coils. Leaving at the zero stud of these 400-ohm coils on the left-hand side, it will pass by a thick wire direct to the left-hand terminal, and so to the other part of the circuit. The two

FIG. 13

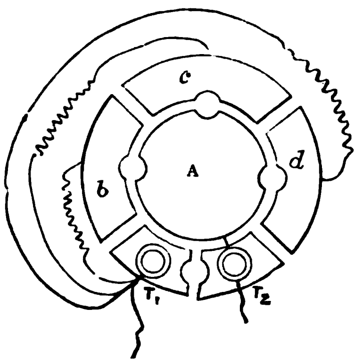


FIG. 14

arms can be readily and independently moved round over the steel studs or points, so that the range of one arm is from 0 to 400 ohms, and that of the other from 0 to 4,000 ohms. The total resistance in circuit with the arms as shown, and all three plugs *in*, is 3,880 ohms. The total range of the instruments is from 10, by multiples of 10, up to 8,430 ohms. Although it is a great advantage that the resistance can be very readily varied, the instrument is somewhat objectionable for delicate measuring purposes, as the contact springs are apt to get weak and the contact unreliable, the resistance then becoming variable.

Another method of casing and joining up resistance coils is shown in figs. 13 and 14. A (fig. 13) is a circular brass plate,

b, *c*, *d* are brass blocks. A tapered hole is provided between each of these outer blocks and the plate A for the usual conical plug. T_1, T_2 are the terminal screws, the latter of which is permanently connected to the brass plate A. One end of each of the three coils is soldered to terminal T_1 and the other end of each to one or other of the outer brass blocks. When it is desired to *insert* one of the resistance coils in the circuit, the plug is placed in the hole which is between the block connected to that coil and the plate A. Thus the operation is the reverse of that previously described, for here we insert a plug to insert resistance, removing it to disconnect the resistance altogether. It is intended that only one coil should be used at a time; and if the plug is placed between terminals T_1 and T_2 the whole box is short-circuited. Fig. 14 shows a box of coils connected according to this method. It is designed for use with a galvanometer as a set of 'shunt coils,' having respectively $\frac{1}{9}$, $\frac{1}{99}$, $\frac{1}{999}$ of the resistance of the galvanometer with which it is intended to be used. And in order that the ratio between the resistance of the shunt coil and of the galvanometer coil may be maintained, notwithstanding variations in temperature, the shunt coils are usually wound with copper wire. (The nature and applicability of shunt coils will be dealt with in Chapter IV.)

For general use as well as for accurate measurements the form of resistance-box shown in figs. 10 and 11 should be used. But where a means of rapidly varying the resistance is necessary, the form shown in fig. 12 is often employed. As we have already remarked, resistance varies considerably with temperature, and consequently the temperature at which resistance coils are measured should be distinctly marked on the case containing them. Then for very accurate tests they may either be brought to that temperature, or a correction made in the reading; but in any case it is known whether any great error is likely to be caused by using them at any particular temperature.

It sometimes happens, however, that sets of resistance coils are required merely for the purpose of dissipating a certain amount of electrical energy. For instance, it becomes necessary, when employing some dynamo-electric machines, to reduce the electrical output in response to a correspondingly reduced demand made upon it by the external circuit; and this can be done by joining

extra resistance in series with the 'magnet coils,' and allowing some of the power to be expended in heating this extra resistance. In such cases it is not necessary to know exactly the value of the resistance in ohms, but it must be divided into a number of small and approximately uniform sections, so that its value can be changed gradually. As the currents employed are, in such cases, frequently very strong, it is important that the coils should be able to transmit such currents and to withstand a considerable rise in temperature without being in any way injured, while at the same time facilities should be afforded for dissipating the heat generated, and thereby keeping the wires as cool as possible. The wire must therefore be left bare, so that the heat generated can be freely dissipated by radiation and convection. Were the wire to be covered with any insulating material, the dissipation by both these processes would be impeded, and there would be the further disadvantage that this sheathing would sooner or later be damaged, if not destroyed. The wire should be of a metal which has a fairly high specific resistance and fusing-point, and should not be liable to deterioration by combining with atmospheric oxygen. For these reasons German silver and tinned or galvanised iron are usually employed, but in special cases platinoid is resorted to. It is essential to select for the supporting frame a material which, while strong, is also non-inflammable and a good insulator, with the smallest possible power of condensing atmospheric moisture upon its surface. In fig. 15 is shown such a set of resistances, suitable for carrying heavy currents. There are two cast-iron end-frames, which are hollow and have slate slabs fitted into them, these slabs being held in position by bolts which pass through both the slate and the iron frame. The slabs, projecting inwards from the frames, carry a series of brass bolts and nuts, on to which are fixed the ends of spirals of bare German-silver wire. Good slate free from metallic veins is a sufficiently effective insulator for the purpose, and the device of passing the connecting bolts right through it and securing them with nuts, instead of trusting to a screw-thread cut in the material, renders it mechanically satisfactory. The frame is completed and made rigid by a pair of iron rods which are secured to the cast-iron ends. The whole of the spirals are joined in series, the two terminals for connection to the external

circuit being fixed on to the slate through holes in the bottom end-frame. The left-hand terminal is joined to the bottom of the left-hand spiral, while the right-hand terminal is connected to the lever of a switch which passes over nine contact pillars rising from the slate bed through an opening in the frame. These pillars

FIG. 15

are connected to the lower junctions of the various spirals, and by altering the position of the switch the spirals can be cut in or out of circuit, in pairs, as desired. There are, of course, many variations of this simple design, the chief aims of which are to secure the best form of contact between the movable arm and the studs, and by means of perforated metallic covers to protect surround-

ing objects from injury while at the same time allowing ample facilities for the dissipation of heat by radiation.

We have seen that whenever a current of electricity flows a certain amount of energy is expended; and it is necessary to be able to measure exactly the amount of energy so expended in any circuit or in any part thereof. The quantity of work performed in raising a mass of one pound through a difference of level of one foot against the force of gravity is generally taken as the unit of mechanical energy, and is known as the foot-pound. The work done in raising any mass through any height is found by simply multiplying together the number of pounds in that mass by the number of feet through which it is lifted. Somewhat similarly we can take as the practical unit of electrical energy the amount expended in transferring a unit quantity of electricity (one coulomb) under a difference of potential of one volt. And by multiplying the number of coulombs which have flowed from one point to another by the difference of potential in volts between those points, we obtain the number of units of electrical energy expended during the passage of the current. The unit of electrical energy, or one coulomb multiplied by one volt, is called a *joule*. As a simple numerical example we may suppose a current of 10 amperes to flow for 5 seconds; then the quantity of electricity passing through the circuit would be 50 coulombs; and if this current were maintained by a potential difference of 8 volts, the amount of energy expended in that time would be $8 \times 50 = 400$ joules.

As a rule, we wish to know the *rate* at which work is being done, in any circuit, rather than the amount which is done in a given time. It is evident that this rate can always be found by dividing the amount of work by the number of seconds taken for its performance; but the same result can be arrived at by multiplying together the potential difference and the rate of transference or flow of electricity, instead of the quantity actually transferred in a given time. Now the rate of flow of electricity is what we know as the current strength, which is measured in amperes. Therefore, if the difference of potential in volts between any two points is multiplied by the resulting current in amperes, the product gives the rate at which energy is being expended, or the rate of working

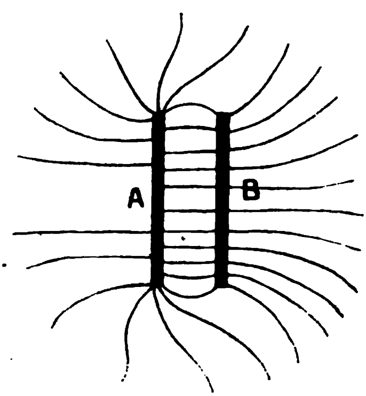
between those two points. The unit rate of working or the unit of *power* is called the *watt*—that is to say, 1 ampere × 1 volt = 1 watt. Therefore, if a difference of potential of 20 volts between the ends of a wire maintains a current of 3 amperes, the rate of working is 3 × 20 = 60 watts.

It is desirable that the relation between mechanical and electrical rates of working should be understood. The mechanical unit is termed the 'horse-power,' and is equal to that rate of working which if continued for one minute would expend 33,000 foot-pounds of energy, or raise 33,000 pounds one foot in height. One horse-power is equal to 746 watts, so that, having calculated the number of watts absorbed in any particular case, on dividing this number by 746 we get the rate of working, or rate of expenditure of energy, expressed in horse-power. This power of 746 watts is, therefore, frequently referred to as the electrical horse-power, but since the general introduction of electric lighting another unit of electrical power has been adopted. This unit is equal to 1,000 watts, or the power expended by 1,000 amperes at a potential difference of 1 volt. A convenient name for this unit is a *kilowatt*, but in practice it is sometimes, although erroneously, contracted into 'unit.' Thus a dynamo-electric machine capable of developing, say, 300 amperes at a potential difference of 200 volts, or 300 × 200 = 60,000 watts, is often referred to as a 60-unit, instead of a 60-kilowatt, machine.

Another very useful and important practical unit is that generally known as the Board of Trade unit, or the kilowatt-hour It is, therefore, a unit of energy, and is equal to 1,000-ampere-volt-hours. Thus, if a current of 5 amperes at a potential difference of 100 volts be maintained for two hours, one kilowatt-hour will have been expended. The amount of energy expended can be easily calculated in Board of Trade units by multiplying together the current in amperes (C), the electro-motive force in volts (E), and the time in hours (T), and dividing the product by 1,000. Thus $\frac{C \times E \times T}{1000}$ = B. of T. units. The public supply of electricity, whether for lighting or power purposes, is usually measured in kilowatt-hours, and the kilowatt-hour is the quantity to which the term 'unit' should be confined.

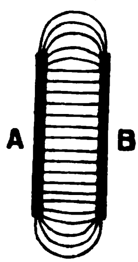
When electricity is communicated to a conductor its potential is raised, and the amount of electricity required to raise the potential, say, from zero to one volt is a measure of its capacity; or, in other words, a conductor has one practical unit of capacity when one coulomb of electricity will raise its potential to one volt. This unit of capacity is called the *farad*, but owing to the fact that the largest conductor ever made would attain a much higher potential than one volt when one coulomb of electricity is communicated to it, a smaller or sub-unit has been adopted in order to avoid the necessity of always using small fractions. The sub-unit is the microfarad, and is equal to one-millionth of a farad, which is usually indicated by the abbreviation mf. It may be interesting to note that the earth has a capacity of about 700 mf., and as the capacity of a sphere varies directly as its radius, it follows that a sphere whose radius is $\frac{1}{700}$ of the earth's radius would if suspended in space remote from all other conductors have a capacity of one microfarad. It is necessary to specify the isolation of the sphere in this case because the proximity of other conductors affects the question very materially. This arises from the fact that when an electrified body is placed in proximity to an unelectrified body, electricity is generated upon the latter by so-called induction. Let us, for example, consider the case of a metal plate A, fig. 16, which has been raised to a certain potential by the communication of, say, a positive charge. In the absence of any other conductor the assumed lines of force will be mostly straight and concentrated around the edge of the plate. If another similar plate B be suspended near and parallel to A, there will be a certain amount of inductive effect produced, the near side of B will be oppositely, that is to say negatively, electrified, and the remote side will

FIG. 16



be positive. The negative electrification of B will be equal in amount to its positive electrification, and the arrangement of the lines of force will be somewhat similar to that shown in the figure. It will be noticed that a portion of the lines emanating from A impinge upon B and appear to pass through it, the remainder of A's lines being more or less distorted but not passing into B. This remainder is known as the 'free' charge, while those lines which pass into B are said to constitute a 'bound' charge. That portion which is in the so-called bound condition does not affect the potential of A, which is dependent solely upon the free lines of force. If it is desired to re-establish the potential which obtained on A prior to the approach of B, more electricity must be communicated to it. In other words, the proximity of B has increased the capacity of A. So long, however, as B remains insulated, or does not envelop A, the effect is not considerable. If, on the other hand, B be now earth connected, practically the whole of the lines of force on A will concentrate themselves on B and will arrange themselves somewhat after the manner indicated in fig. 17. In other words, nearly the whole of the charge on A has been transferred from the free to the bound condition, and the potential of A has been reduced almost to zero, and a second and much greater charge will be necessary in order to raise the potential of A to its previous value. The earthing of B is equivalent to bringing A and the earth itself correspondingly close together. It has been stated that the capacity of a conductor varies as the quantity of electricity required to raise its potential from zero to unity, or, if K represents the capacity and V the potential

FIG. 17



$$K = \frac{Q}{V}, \text{ or } V = \frac{Q}{K}.$$

As in the case of a sphere the several parts of its surface are equidistant from its centre, it follows that the average distance of those parts from a given external point, but close to its surface, will be equal to the distance from the centre of the sphere to that point; it is said that the charge on a sphere behaves as though it were

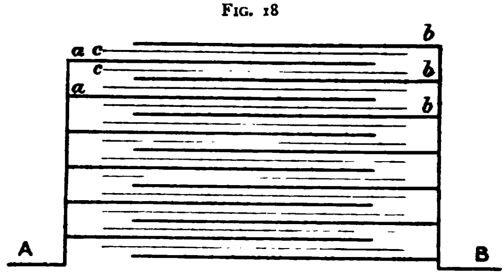
located at its centre, and this explains in a measure the fact that the capacity of a sphere is directly proportional to its radius, or, K varies as *r*. When, however, the conductor is not spherical, or is adjacent to other conductors, the problem is much more complicated. This will be evident if the experiment with the two plates illustrated in figs. 16 and 17 be again considered.

Such an arrangement as that indicated in figs. 16 and 17, consisting of two conducting bodies separated by an insulator, is known as a condenser, of which the well-known Leyden jar was the earliest example. Here, however, another important element enters into the question. The medium separating the two plates in fig. 17 is air, which in a dry state is almost a perfect insulator, and in which, owing to its being a gas or mixture of gases, the particles have no approach to continuity, as in the case of a solid body. When a liquid insulator, and to a greater extent when a solid insulator is interposed between the conducting plates, electrostatic induction takes place much more freely and the capacity of the condenser is increased accordingly. The insulating medium which separates the two conductors of a condenser is called a dielectric, and the induction which a dielectric permits as compared with dry air under similar conditions as to potential and dimensions is known as the specific inductive capacity. Thus the specific inductive capacity of air being taken as unity, that of glass is from 2 to 5 for flint glass, from 5 to 10 for crown glass, and of paraffin wax is from 1·9 to 2·3. This means that if in a given condenser such as that indicated in fig. 17 we substitute crown glass for air 10 times as much electricity may be required to raise the potential of the condenser from zero to unit potential than would be necessary with air, while if paraffin wax were used about 2·1 times as much electricity would on the average be required.

There is another interesting phenomenon observable with liquid or solid dielectrics, and that is that when a charge of electricity is communicated to the condenser the potential gradually falls for some time. If a source of E.M.F., such as a number of primary cells joined together, be kept connected to the condenser, it will be noticed that electricity will continue to pass into the condenser for an appreciable time. Obviously, as the metal plates forming the conductors have very high conducting

properties the charge of electricity should, in the absence of any disturbing factor, be instantaneous, and the condenser should promptly attain and maintain its normal potential. The effect is apparently due to the charge, when it is communicated to the conductors, gradually soaking into the pores of the dielectric as a result of the attraction between the two opposite charges, or, as we may otherwise put it, as a result of the effort of the lines of force to shorten themselves. The consequence of the soaking-in is also seen on the discharge of a condenser, and for the purpose of demonstrating this a Leyden jar or other condenser with a glass dielectric is very useful. If such a condenser be charged to a high potential and then discharged a spark will pass. Had the dielectric been dry air the discharge would have been complete,

FIG. 18

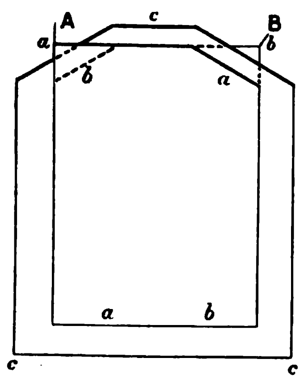


but with glass it is only partial, for after waiting a few seconds another but feebler discharge can be observed. This is due to the charge which had soaked in under the high potential, soaking out again when that potential is reduced. The practical consequence of this is that in testing the capacity of insulated cables, consisting, for example, of a copper conductor surrounded by vulcanized indiarubber or by gutta-percha, it is specified that the cable shall be immersed in water up to but not including its extremities for a period of twenty-four hours so that the soaking effect, or the 'electrification' of the dielectric shall have attained a maximum before the final test is taken.

In building up a condenser for practical purposes paper saturated with paraffin wax is most frequently employed, and the high specific inductive capacity of the wax is in most cases advan-

tageous, but great care has to be taken in ensuring the necessary insulation between the conductors, which should be as thin as possible. A modern condenser consists therefore of a number of sheets of tinfoil, separated by sheets of paraffined paper. The alternate sheets of tinfoil are connected together, the result being equivalent to a single pair of very large sheets; fig. 18 illustrates the arrangement. The sheets *a a* connected to a terminal at A form one side or plate of the condenser, and the sheets *b b b* connected to B form the other side. The interleaving sheets of paper *c c* extend beyond the tinfoil so as to prevent the charge from sparking across between *a* and *b*. In practice the sheets are frequently cut as shown in fig. 19, where *c c* represents a sheet (but generally two sheets are used to ensure insulation) of paraffined paper with the tinfoil sheet *a a a* resting upon it, the corner piece A extending beyond the paper, while a similar sheet *b b b* lies beneath the paper but with its corner piece exposed on the side B. When the requisite number of pairs have been built up, the corners at A and B respectively are clamped together. There are other methods of shaping the tinfoil and paper sheets, but all have the same object—namely, to provide two extensive conducting surfaces effectively insulated from each other. The paper must be thoroughly dried and well served with melted paraffin wax to increase the insulation and prevent the subsequent absorption of moisture. Usually the condenser is made up so as to be below the required electrical capacity, and while the wax is still warm it is placed in a press and squeezed together until the greater proximity of the metal sheets raises the capacity to the required value. Great care must be taken in selecting and treating the paper. It must be thin and absolutely free from holes (which very few thin papers are), otherwise there will be considerable risk of the charge sparking through, and then not only is the charge

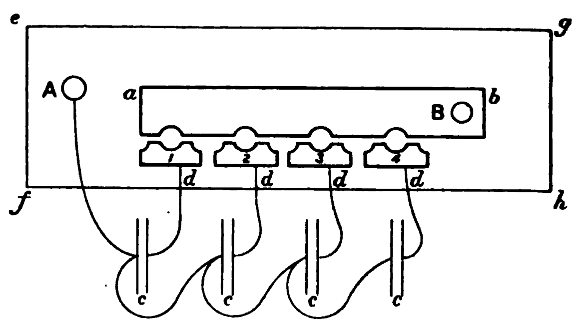
FIG. 19



lost, but the condenser is permanently damaged. For this reason banknote paper is usually employed. The series of sheets of tinfoil and paper make with the cooled paraffin wax a solid mass, known technically as a condenser plate.

As a rule the plates are made up to some definite capacity, say one microfarad each, and a number of plates are then combined to produce any other desired capacity. The majority of condensers consist of a series of capacities, such as 1, 2, 3, and 4 mf., the making up of which would involve the use of ten one-microfarad plates, the whole clamped between two iron plates and enclosed in a wood or other convenient box, fitted on the top or at the end of which is an ebonite plate similar to that used for resistance boxes (see fig. 10). The connections are, however, arranged differently, as may be seen from fig. 20, where A, B are the

FIG. 20



terminals to which the external wires should be connected. The condenser plates *c c c c* are all connected on one side to terminal A, the other sides being connected to one or other of the brass blocks *d d d d*. Terminal B is mounted upon a substantial brass strip *a*, *b*, which together with the brass blocks and terminal A are mounted on the ebonite strip or plate *e f g h*. The insertion of pegs between *a b* and the brass blocks introduces into the circuit any required capacity from 1 to 10 mf.

When the condenser is required to carry very high voltages, or when there is considerable power as well as potential to be dealt with, mica is frequently employed instead of paper, but mica is

thicker than paper, and as the tinfoil sheets cannot therefore be brought so close together, more sheets have to be used in order to provide a similar electrostatic capacity.

It will probably have become evident to the student that the building up of condensers in the manner described is a costly matter, the whole of the work having to be done by hand. The thinnest tinfoil obtainable is also, in view of the fact that only a metal surface is necessary, thicker than is actually required for the purpose. Attempts have been made to simplify the manufacture by rolling up two continuous strips of tinfoil, but the thinnest foil can only be made in lengths of three or four feet, while the use of thicker foil would increase the cost, as well as the weight and bulk of the condenser. Mr. G. F. Mansbridge has devised a simpler and much cheaper form of construction; he uses paper coated on one side with metallic tin in a finely divided state, the paper forming the dielectric and the metallic coating forming the plate; such paper can be obtained in strips of as great a length as desired. The material known as 'tinfoil paper' commonly used for wrapping tea, &c., has been found to be fairly suitable for the purpose and is obtainable in large quantities at a cheap rate; this tinfoil paper is prepared by applying to the paper finely divided tin in the form of a paste, suitable means being provided to ensure a sufficiently even distribution of the paste. The pasted paper is afterwards passed under heated calenders so as to burnish and consolidate the coating of tin. The use of a sufficient quantity of tin and the proper calendering of the paper, so as to render the conducting surface practically continuous, are, however, essential in the manufacture of satisfactory tinfoil paper for condenser purposes.

Condensers might be constructed on this principle by applying two coatings of tin to the opposite sides of a single sheet of paper, an uncoated margin being left; the coated strip being then rolled up with an uncoated strip in the same manner as with two coated strips; but in order to ensure a high insulation it is the practice to use two single coated strips of paper interleaved with thin unfoiled paper so as to obtain a double thickness of dielectric.

After sufficient lengths of coated and uncoated paper have been coiled up, the roll is removed from the mandrel and is then

dried for about 24 hours at a temperature of 240° to 250° F. It is then placed in a vacuum pan containing melted paraffin wax sufficient to cover the 'plate'; the air is then exhausted, and a vacuum as high as is practicable is maintained for two hours, the temperature of the wax being kept at 100° C. On removal from the pan, the superfluous wax is removed with a wood stick or tool, and the roll is transferred to a water-cooled screw press for about five minutes, whence it emerges as a flat compact slab or 'plate,' the edges being freed from any superfluous wax that may remain by rubbing them lightly over a 'hot-plate.' The insulation resistance (see Chapter V.) of a microfarad plate is about 1,000 Ω. The coated paper is obtainable in continuous reels weighing from 12 to 14 lb. and of any width, 6½ inches being a convenient size. Experience has shown that the heavy pressure to which the paper is subjected in the process of calendering forces through the pores of the paper minute particles of metal, which either form an electrically conducting path from one side of the paper to the other, or partially bridge the space between the two sides of the paper, and thereby render such places liable to break down when the opposite sides of the paper are charged to a high potential difference. Faults of this nature are ingeniously removed by passing the paper over two sets of conducting rollers, one set being in contact with the foiled surface and the other with the plain side of the paper. The rollers on the opposite sides of the paper are connected respectively with the poles of a battery or other source of electro-motive force, and when a defective place passes over the roller which is in contact with the plain side of the paper, an electrical current is completed through the defective place, and a sufficiently high electro-motive force being used, a momentary current of considerable strength passes and fuses or volatizes the thin layer of metal immediately adjacent to the defect, and renders it, over a small area, discontinuous and non-conducting. From an electric-light engineer's point of view, this self-sealing property is of importance, for it has been experimentally demonstrated that if pins be pushed into the plate so as to short-circuit it at a number of places, and if the pins be withdrawn, the next succeeding current of appreciable strength speedily breaks down the short circuits by fusing the conducting material

in the immediate vicinity of the pinholes. This is a phenomenon which could not be reproduced in the case of ordinary tinfoil condensers. When good thin interleaving paper is used, the area of the foiled surface required for a condenser is about 2,500 square inches per microfarad.

It will on reflection be evident that a submarine cable, or a subterranean cable laid in iron pipes, or a lead-covered cable is to all intents and purposes an effective condenser, in which the conductor corresponds to the plate A in fig. 17, and the metal sheathing of the submarine cable, or the iron pipe of the subterranean india-rubber-covered cable, or the lead sheathing of the third type of cable, corresponds to the plate B.

It may interest the student to learn that the capacity of a submarine cable is usually 0·3 mf. per mile; of a paper insulated subterranean telegraph cable 0·1 mf. per mile, and of an open telegraph wire, with the air between it and the earth as the insulating sheet (or dielectric), 0·03 mf. per mile. The condenser finds an important application in connection with alternating currents, and its action may be explained as follows: when connected across the terminals of a machine supplying an alternating E.M.F. the condenser plates have in turn a positive and negative potential, and consequently a corresponding positive and negative charge—that is to say, when either plate changes from a positive to a negative potential, the charge on that plate reverses its sign also, and therefore a charge of electricity pulsates backwards and forwards in the circuit, and this pulsating charge constitutes the alternating current.

The units described in this chapter and others which will be referred to in subsequent chapters are those which are employed in practice by electrical engineers. No effort should therefore be spared to master the simple relation existing between the ampere, volt, ohm, horse-power, kilowatt, &c. But it is advisable to know the method by which the various electrical units have been evolved, for they have not been selected arbitrarily, like the pound, yard, and gallon, but are built up on the fundamental conceptions of length, time, and quantity of matter, and are inseparably linked together. Perhaps the simplest measurable quantity which we can conceive is that of length, and in deciding upon a unit of

length an effort was made to select some unalterable natural distance. The length of an earth quadrant—that is, the distance from the equator to the pole along a meridian—was agreed upon, and one ten-millionth part of this taken as the practical standard of length, and called a metre. The original measurement of the earth-quadrant proved to be considerably in error, and consequently the simple relation between it and the metre was upset. But the metre thus determined is retained as the standard of length, and one-hundredth part of this length, called one centimetre, is taken as the basis of the units upon which the system now to be briefly described has been reared. A square centimetre is the area contained in a square each of whose sides is one centimetre, and a cubic centimetre is the volume contained in a cube each of whose edges is one centimetre in length.

The next unit required is that of mass, or quantity of matter, and it should be remembered that the force of gravity acts upon every body in exact proportion to its mass, or the quantity of matter in it, independently of its size; therefore, what we know as the weight of any substance is exactly proportional to its mass. The unit of mass is called the gramme. It is equal to the mass contained in a cubic centimetre of pure water at its maximum density, *i.e.* at a temperature of 4° Centigrade.

The third unit, that of time, is called the second. It is the length of time known generally by that name, and is the 86,400th part of a mean solar day; that is to say, there are 86,400 seconds in a day as we ordinarily measure time by the clock.

The great value of a system built upon such units as those described is that it is always possible to recover any one of them, and so to construct or verify the system, if necessary, although the process is, no doubt, difficult and tedious. The term 'absolute' has been applied to such a system, but it is not easy to see the precise application of the word. It is usual, and certainly better, to refer to it as the centimetre-gramme-second, or, briefly, the C.G.S. system.

The next conception in order of simplicity is that of the rate at which a mass of matter changes its relative position, or the velocity with which it moves. Velocity is estimated by dividing

the distance in centimetres through which a body moves by the time in seconds taken to travel that distance. The unit is a velocity of one centimetre per second every second.

A mass of matter cannot, by any property belonging to it, change its position, or its state of rest or motion by itself. That which is competent to move, stop, or vary the motion of a mass of matter is called force, and the greater the force, and the longer the time during which it acts, the greater will be the increase or decrease in the velocity of a given mass. The unit of force is called the *dyne* : one dyne is that force which, by acting upon a mass of one gramme during one second, can impart to it an acceleration of one centimetre per second during every second that the force is maintained.

When the position of a body is changed in opposition to any resisting force, work is done or energy expended, the amount being estimated by multiplying together the force overcome and the distance through which it is overcome. The unit of work is called the *erg*, and it is that work which is done when a force of one dyne is overcome through a distance of one centimetre : the energy expended is in every case equal to the work done; therefore the erg is also the unit of energy. We have seen that the *practical* unit of work, or expenditure of energy, is the joule; and one joule is equal to ten million ergs. Consequently, the practical unit of power, or rate of doing work, called the watt, is equivalent to ten million ergs per second.

Current strength is measured by the quantity of electricity which flows past any point in a circuit per second. The C.G.S. unit is that current strength which, when a conductor carrying this current forms a circle of one centimetre radius, exerts a force of 2π dynes upon a unit magnetic pole placed at the centre of the circle—that is to say, when each centimetre of the circular path contributes a force of one dyne. The conditions of this unit will, however, be better understood after studying Chapter IV. The practical unit which is called the 'ampere' is equal to one-tenth of this C.G.S. unit. The value of the ampere has also been defined by another method; it is that current which, when passed through a solution of nitrate of silver, deposits the silver at the rate of 0·001118 of a gramme per second.

The C.G.S. unit quantity of electricity is that quantity conveyed by unit current in unit time. The practical unit, the coulomb, is therefore also one-tenth of the C.G.S. unit.

The unit difference of potential between two points exists when one erg of work has to be performed in urging one unit of electricity against that potential difference, or when one erg is expended by the flow of one unit of electricity from the one point to the other. The volt or practical unit is 100,000,000 times the C.G.S. unit.

Unit resistance exists when unit difference of potential causes a current of unit strength to flow through it. It follows, therefore, that the ohm is equal to 1,000,000,000 C.G.S. units.

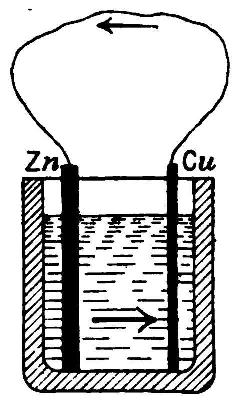
The units which chiefly claim our attention are those of current, quantity, potential difference, and resistance. It is not possible to provide an invariable physical standard of any one of these, except resistance, which fact to a certain extent increases the importance attached to the unit of resistance. As has been pointed out, a definite physical standard, in the form of a column of mercury of certain dimensions, has been selected to represent the ohm. There are certain other derived units which the student is scarcely yet in a position to appreciate, but which it is necessary that he should be made acquainted with. It is therefore proposed to introduce them in subsequent chapters as opportunities present themselves.

CHAPTER III

PRIMARY BATTERIES

A CURRENT of electricity can be maintained in a number of ways. One of these is by means of primary cells. A primary cell consists essentially of a vessel containing a saline or acidulated solution, in which are immersed two solid conducting bodies, one of which is more assailable than the other by the liquid. When two or more cells are joined together to increase the effect the combination is known as a battery.

FIG. 21



Primary cells can be divided into two classes, viz. (*a*) single-fluid, or those in which only one solution is used ; and (*b*) double-fluid, or those in which two solutions are employed.

The single-fluid cells are typified by the 'simple cell,' which was referred to on page 2, and which consists of a glass or earthenware vessel (fig. 21) nearly filled with water acidulated with a small proportion of, say, sulphuric acid, and containing a piece of zinc, Zn and a piece of copper, Cu. On connecting the plates externally by a piece of wire, and thereby allowing the current to flow, the surface of the zinc is attacked by the solution, and sulphate of zinc is formed, hydrogen gas being liberated in the liquid at the surface of the copper plate.

This reaction may be represented by an equation, thus:—

$$\underset{\text{Zinc.}}{Zn} + \underset{\text{Sulphuric acid.}}{SO_4H_2} = \underset{\text{Sulphate of zinc.}}{SO_4Zn} + \underset{\text{Hydrogen.}}{H_2}$$

No chemical effect whatever is produced on the surface of the copper plate, and this state of affairs—that is to say, the oxidation of one plate and the absence of any action upon the other plate—is characteristic of all primary cells. The plate which is more or less dissolved is called the positive plate, the other being called the negative plate.

As the hydrogen deposited on the negative plate does not enter directly into chemical union with copper, or indeed with any other of the simple metals, it in this case remains in the gaseous state. The resultant changes present the appearance of only the acid portion of the solution being affected, while the water remains constant and unchanged. The water is, however, essential, and the probable explanation is that in the chemical changes it gains from the acid the exact counterpart of what it gives to the zinc. The hydrogen is released in a definite ratio to the amount of zinc dissolved. In fact, we may take it as an established law that the ratio between the weight of zinc dissolved and that of the hydrogen, &c., released by the passage of the current is invariable, and that this ratio is dependent upon the respective 'electro-chemical equivalents.'

We see by the above equation that for every atom or equivalent of zinc dissolved or converted into sulphate of zinc two atoms of hydrogen are liberated. An atom may be defined as the smallest possible quantity of any simple substance capable of entering into or passing out of chemical combination; and it will be seen on referring to the table (on the next page) of atomic weights (or of the relative weights of individual atoms) of some of the more important substances, that an atom of hydrogen weighs less than one of any other substance.

It will also be observed that an atom of zinc weighs sixty-five times as much as an atom of hydrogen. The meaning of the equation, therefore, is that for every sixty-five parts by weight of zinc dissolved two parts by weight of hydrogen are liberated: consequently, if we again regard the relative deposition of hydrogen as the standard, the weight of zinc dissolved will be 32·5 times as much, or, in other words, the chemical equivalent of hydrogen being unity, that of zinc is 32·5. The chemical equivalents of the other elementary bodies enumerated in the table

TABLE OF ATOMIC WEIGHTS AND EQUIVALENTS

Elements	Symbol and Valency	Atomic Weight	Chemical Equivalent	Electro-chemical equivalent (Milligrammes per Coulomb)
ELECTRO-POSITIVE				
Hydrogen	H^1	1·	1·	·010384
Potassium	K^1	39·04	39·04	·40539
Sodium	Na^1	22·99	22·99	·23873
Aluminium	Al^3	27·3	9·1	·09449
Magnesium	Mg^2	23·94	11·97	·12430
Gold	Au^3	196·2	65·4	·67911
Silver	Ag^1	107·66	107·66	1·11800
Copper (Cupric)	Cu^2	63·	31·5	·32709
,, (Cuprous)	Cu^1	63·	63·	·65419
Mercury (Mercuric)	Hg^2	199·8	99·9	1·03740
,, (Mercurous)	Hg^1	199·8	199·8	2·07470
Tin (Stannic)	Sn^4	117·8	29·45	·30581
,, (Stannous)	Sn^2	117·8	58·9	·61162
Iron (Ferric)	Fe^1	55·9	18·64	·19356
,, (Ferrous)	Fe^2	55·9	27·95	·29035
Nickel	Ni^2	58·6	29·3	·30425
Zinc	Zn^2	65·	32·5	·33696
Lead	Pb^2	206·4	103·2	1·07160
ELECTRO-NEGATIVE				
Oxygen	O^2	15·96	7·98	·08286
Chlorine	Cl^1	35·37	35·37	·36728
Iodine	I^1	126·53	126·53	1·31390
Bromine	Br^1	79·75	79·75	·82812
Nitrogen	N^3	14·01	4·67	·04849

have been calculated in a similar way. The 'electro-chemical equivalents' are obtained by multiplying together the weight of the hydrogen liberated by one coulomb of electricity and the chemical equivalent of each of the other elementary bodies.

The liberated hydrogen, in consequence of its low specific gravity, exhibits a tendency to rise through the water and escape into the air. Only a portion, however, of the gas escapes in this way, a large proportion adhering to the copper plate and forming, as it were, a gaseous film over the metallic surface. This accumulation, due to a variety of causes, is facilitated by the opposite electrical conditions of the copper and hydrogen, which cause a mutual attraction to set it. There is a double effect of the accumulation which soon becomes apparent, for a gradual diminution in the current sets in, consequent first on the decrease in the copper surface exposed to the liquid (which involves a

proportional increase in the internal resistance of the cell), and, secondly, on the tendency on the part of the positively electrified hydrogen film to set up a contrary current through the cell. When this condition is arrived at the cell is said to be polarised —that is to say, the two surfaces, zinc and hydrogen, are brought to nearly the same potential, and as a consequence the current strength is correspondingly reduced. The effect of the passage of a current being, therefore, a reduction of the effective electro-motive force of the cell, such a combination is unsatisfactory for purposes requiring a continuous and uniform current—that is to say, a current of 'constant' strength.

To overcome this objection Smee constructed a cell the peculiarity of which consisted in the nature of the surface of the negative plate. It had been ascertained that a smooth surface allows a much more rapid accumulation of hydrogen than does a roughened surface. Accordingly, he used for his negative plate a thin sheet of silver covered with a platinum deposit in a state of very fine division, so that an irregular surface was produced, by means of which the hydrogen particles rose through the liquid more nearly in proportion to the rate of production. So treated the plate is known as platinised silver. Zinc was employed for the positive plate, the solution being 1 of acid to 10 of water. The cell has a higher electro-motive force because of the substitution for copper of a more electro-negative plate. When the cell is made of abnormally large proportions, it approximates even more nearly to the condition of a constant cell, and is used as such by many electroplaters.

A more important cell is the Leclanché (fig. 22), in which a zinc rod, z, is used as the positive plate, while the negative plate c takes the form of a slab or narrow plate of prepared carbon. This prepared carbon is made by subjecting to considerable pressure, at a high temperature, a mixture of powdered carbon and some treacly substance, which is employed for cementing the carbon particles. The carbon plate is placed inside a vessel of porous (unglazed) earthenware, which is then filled with a mixture of crushed, but not powdered, carbon and black oxide of manganese. The latter should be granular, of about the size of peas, care being taken to exclude powder or dust. The

outer vessel, G, is generally of glass, which enables the condition of the cell to be observed without removing any of the parts, and which affords facilities for obtaining a high insulation. The liquid consists of a saturated solution of sal-ammoniac, or chloride of ammonium, the porosity of the inner jar allowing the solution to diffuse itself somewhat freely, and so to moisten the mixture of carbon and black oxide.

FIG. 22

When the cell is in action the zinc combines with the chlorine of the sal-ammoniac, forming zinc chloride, simultaneously releasing hydrogen and ammonia, the latter dissolving in the water until a saturated solution is obtained—that is to say, until the solution holds as much as it can support—after which it escapes as a gas. It may, however, be remarked that water is not saturated with ammonia until it has absorbed 727 times its volume of the gas at a temperature of 15°·5 C. or 60° F. The hydrogen so far remains free. It is, however, ultimately released inside the inner vessel, and there it deprives the manganic oxide of some of its oxygen, forming water and sesqui-oxide of manganese.

The entire action may be represented by an equation thus:—

$$\underset{\text{Zinc}}{Zn} + \underset{\text{Sal-ammoniac.}}{2NH_4Cl} + \underset{\text{Manganic Oxide.}}{2MnO_2} = \underset{\text{Zinc Chloride.}}{ZnCl_2} + \underset{\text{Ammonia}}{2NH_3} + \underset{\text{Water}}{OH_2} + \underset{\text{Sesqui-oxide of Manganese}}{Mn_2O_3}$$

There is frequently, however, a subsequent or secondary reaction between the zinc chloride and the other constituents of the solution, resulting in the formation of what are called double salts, which tend to reduce the efficient working of the cell.

It will be seen, from a study of the equation, that the working of the battery results in the gradual absorption of the zinc and the

decomposition of the sal-ammoniac, &c., which accordingly require replenishing at times. A whitish-yellow turbidity in the solution indicates the presence of an excessive amount of zinc chloride in proportion to the amount of sal-ammoniac, which latter should then be increased; but it is preferable to remove a portion of the solution and then fill up with water before adding the sal-ammoniac.

Considerable care is taken in the construction of this cell. As both sal-ammoniac and ammonia are corrosive and attack copper, brass, &c., all the exposed metallic surfaces should be well served with pitch, paraffin wax, or some other non-corrosive and impervious material.

It is the general practice to drill two small holes through the upper extremity of the carbon, and, after raising the end to a high temperature, to dip it into melted paraffin wax. It is subsequently placed in a mould into which molten lead is run, a terminal or binding-screw being at the same time cast into the leaden cap thus formed. The function of the wax is to close the pores in the upper portion of the carbon, and so to prevent the ammoniacal solution from creeping up to the leaden cap. Lead is interposed between the carbon and the brass terminal because it is the least assailable of the ordinary metals. Pitch is run over the carbon-manganese mixture to keep the mixture and the carbon rod in position, holes being made in it, however, to permit any hydrogen or other gases that may be formed to escape, or any air that might be in the pot to be expelled when the pot is placed in the solution. The upper parts of the porous pot, and the zinc rod and the connections, are likewise coated with pitch.

The electro-motive force of this cell is about 1·5 volt, or nearly twice that of the simple cell, while owing to the large surface exposed, more particularly at the negative plate, the internal resistance is also low. The chief objection to the cell as ordinarily made is the rapidity with which it polarises and so becomes temporarily useless, owing probably to the fact that hydrogen is liberated faster than the manganic oxide can be decomposed. That this is the case is in a measure demonstrated by the fact that if the cell is allowed to stand idle for a brief interval of time it will again yield its full current. The defect, although very marked

when the resistance of the circuit is low, is reduced to a minimum when the resistance is high, because the current is then feeble and the chemical reactions proportionately less. A nearer approach to a constant current can, however, be maintained on a comparatively low resistance circuit by substituting a zinc cylinder for the rod and enlarging the carbon plate.

The constituents of the cell remain inactive when the cell is idle; and this is a point of very considerable importance, for it means that there is no wasteful action in the cell, such as there is in practically every other type of cell—at least, in every cell in which an acid plays a part. Cleanliness is necessary in dealing with the Leclanché, or, indeed, any other form of cell, and it is essential that the containing vessel, whether of glass or earthenware, should be kept dry externally. The latter desideratum is usually accomplished by coating the upper portion of the outer surface of the vessel with pitch or some other such substance as will not readily permit the liquid to 'creep' over its surface, for the salt (sal-ammoniac) has a strong tendency to crystallise out. Should the solution be allowed to creep, we have to contend not only with the waste of salt so occasioned, but also with the 'leakage' of current that would take place over the moistened external surface.

There is a modification of the Leclanché which is of some importance, and which is known as the 'agglomerate' Leclanché. The negative element consists of a carbon plate or block, having in contact with it blocks of agglomerated carbon and manganese. The latter are prepared by intimately mixing 40 parts of manganic oxide, 55 parts of gas carbon, and 5 parts of gum lac resin, and submitting the mixture, placed in a steel mould, to a temperature of 100° C., applying at the same time considerable hydraulic pressure. The result is a solid compact mass, and, as the chief function of the porous pot in the older type is to support the mixture of crushed carbon and manganic oxide, it is apparent that that vessel, which materially increases the internal resistance of the cell, can be dispensed with. Indiarubber bands placed round the agglomerated blocks (which in their turn embrace the carbon block) keep the whole of the compound negative element together.

In the earlier forms of agglomerate cell rectangular blocks of agglomerated manganic oxide and carbon were held against the two faces of a flat plate or block of carbon, and the indiarubber bands holding the three blocks together were specially made so as to hold also the zinc rod, which was of the usual type. But a much better form is that known as the 6-block agglomerate cell (fig. 23), which is very extensively used. The negative element consists of a block of carbon with six fluted sides, capped with lead and fitted with a terminal after the top of it has been steeped in hot paraffin wax. In each of the sides is laid a round stick of the agglomerated carbon and manganic oxide, the whole being wrapped round with a piece of coarse canvas, and held in position by a couple of stout indiarubber bands. It is essential that the agglomerate rods should closely fit into the flutes throughout, in order to secure a low and uniform internal resistance. The canvas does not, of course, prevent intimate contact between the rods and the solution, nor does it appreciably increase the internal resistance of the cell, its function being simply to prevent pieces of the agglomerate rods falling out and 'short-circuiting' the cell, by joining the positive and negative elements together.

FIG. 23

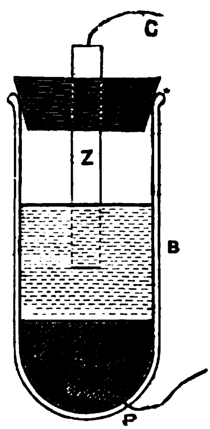
Instead of employing a zinc rod for the positive element, a large piece of sheet zinc (about $\frac{1}{8}$ inch thick) is rolled into a cylinder, the approaching edges being, however, kept a quarter of an inch or so apart to allow the free circulation of the solution. In consequence of the very large increase in the amount of the surfaces thus exposed to the liquid, the internal resistance is very considerably reduced, polarisation being also to a very great extent prevented or impeded. Much larger and more prolonged currents

can, therefore, be taken from this than from the older type of cell.

The electro-motive force of any one of the many forms of Leclanché cell may be taken as being approximately 1·5 volt, while the internal resistance may range from 0·25 to 3 or 4 ohms, according to the size of the elements and the construction of the cell.

The 'Standard' cell (fig. 24), invented by Mr. Latimer-Clark, is an important one. It is designed solely as a standard of electro-motive force, and is largely employed for purposes of measurement. It may be made in a small glass vessel, such as a short wide test-tube, a layer of pure distilled mercury, M, being employed as a negative plate, which covers the bottom of the glass vessel to a depth of half an inch or so. Over this is placed the 'liquid' or electrolyte, which consists of a thick paste, B, made by mixing mercurous sulphate with a saturated solution of zinc sulphate. The positive element is a rod of pure distilled zinc, Z, which dips into the paste. It is usual to seal the battery by means of a cork and marine glue or by cement. Connection is made with the zinc by means of a copper wire, C, soldered to the upper end of the zinc rod, which passes through the stopper S. A platinum wire, P, fused into the bottom of the vessel, makes contact with the mercury, or the platinum wire may be passed through a glass tube placed inside the glass containing-vessel and closed at its lower end, the projecting end of the wire being below the surface of the mercury. The cell is then in a more convenient form for immersing in water with a thermometer in order to ascertain its actual temperature.

FIG. 24



It is highly essential that the constituents of the cell should be absolutely pure; hence the necessity for re-distilling the zinc and mercury. The mercurous sulphate can be made by dissolving pure mercury, placed in excess, in hot pure sulphuric acid. The sulphate is an insoluble white powder, and should be well

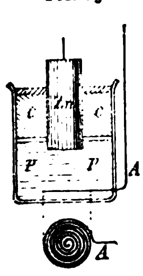
washed with distilled water before it is mixed with the zinc sulphate, to remove any trace of the mercuric sulphate or of free acid. The mercuric contains a smaller proportion of mercury than the mercurous sulphate, and on the addition of water imparts to it a yellowish tinge.

The chemical action which takes place during the passage of a current is to decompose the mercurous sulphate, adding the mercury released to that already in the vessel, an equivalent of zinc being simultaneously dissolved off the positive rod, thus increasing the amount of sulphate of zinc in the paste.

The electro-motive force of this cell is 1·434 volt, and is exceedingly uniform, provided that the cell is never allowed to send a current of any appreciable strength. Should the resistance of the circuit be low, the current becomes proportionally strong, and the mercury salt is not then capable of being decomposed at a corresponding rate, whence polarisation sets in and the electro-motive force falls in consequence. Under the most favourable conditions, a cell which has in this way been lowered in its electro-motive force takes a considerable time to recover, and frequently the injury is permanent—that is to say, the cell becomes practically useless. The electro-motive force decreases with an increase of temperature, the rate being about 0·08 per cent. per degree Centigrade.

The commercial form of Clark cell constructed after the plan of Dr. Muirhead is illustrated in fig. 25. Instead of using a layer

FIG. 25



of mercury, the platinum electrode A, fused through the glass containing-vessel, is made of a long piece of wire which is coiled into a close flat spiral and coated with mercury, either by heating and then immersing it in a mercury bath, or by heating the mercury and the platinum together. The spiral is then embedded in the paste, composed of pure mercurous sulphate and a saturated solution of pure zinc sulphate, *p*. The pure zinc rod, *Zn* is dipped into the paste, and a cement stopper, *c*, holds the whole firmly together, so that the cell is made more portable than that shown in fig. 24, which has the disadvantage that the constituents of the cell are liable to become mixed if it is

not used very carefully. The mercury deposited on the platinum spiral is sufficient to form and maintain the negative element or 'plate,' a considerable layer of mercury not being really essential. It is evident that the internal resistance of such a cell is very high; but this is not a disadvantage, the cell being used only as a standard of electro-motive force.

Fig. 26 shows the method employed for casing in. A cylindrical brass case with an ebonite cover is used, and contains two cells which can be balanced one against the other to test their relative electro-motive force, or they can be used together and give a double electro-motive force. A thermometer is likewise provided, the bulb being inside and the tube bent so as to lie over the scale on the cover. This is an important though simple innovation, and assists in the avoidance of an error due to a varying temperature. To avoid any error due to polarisation it is better to employ the cell only for the purpose of making an effort to send a current and noting the maximum potential difference it can produce, which will, of course, be equal to the electro-motive force of the cell. For example, it may be used to charge a standard condenser, or in conjunction with the 'potentiometer' described in Chapter VI.

FIG. 26

In recent years another form of standard cell has been introduced and is very extensively employed, chiefly because of its practically uniform E.M.F. at all ordinary temperatures, and of the fact that it is not so liable to injury as a consequence of its being allowed to send an unusually strong current. It is known as the Weston Cadmium cell and has mercury for its positive plate or electrode, and an amalgam of cadmium—that is to say, a mixture made by dissolving $12\frac{1}{2}$ parts by weight of cadmium in $87\frac{1}{2}$ parts

of mercury, for its negative electrode. The solution or electrolyte consists of a saturated solution of cadmium sulphate, with a reserve of solid cadmium sulphate within the cell. A paste consisting of solid mercurous sulphate, mercury, and cadmium sulphate rests on the positive electrode. All the constituents must of course be chemically pure, and special precautions are taken to ensure this as in the case of the Clark cell.

The only other form of single-fluid battery which we need notice is that in which a solution of bichromate of potash is employed.

The solution consists of 1 part by weight of bichromate of potash, 2 parts of good sulphuric acid (of 1·8 specific gravity), and 12 parts of clean water. The bichromate of potash is first pulverised and then added slowly to the acid, stirring all the time. This converts the bichromate of potash into chromic anhydride and potassic sulphate, which precipitates in a crystalline formation, the chemical reactions being indicated by the equation:

$$\underset{\text{Bichromate of potash.}}{K_2Cr_2O_7} + \underset{\text{Sulphuric acid.}}{7SO_4H_2} = \underset{\text{Chromic anhydride.}}{2CrO_3} + \underset{\text{Potassic sulphate.}}{K_2SO_4} + \underset{\text{Water.}}{OH_2} + \underset{\text{Sulphuric acid.}}{6SO_4H_2}$$

Water is then added slowly, when the crystals are dissolved and the chromic anhydride converted into chromic hydrate or acid (H_2CrO_4) by the absorption of water, a quantity of the water being taken up, with the evolution of a considerable amount of heat. The energy with which sulphuric acid unites with the water is very great, and it is this fact that necessitates the slow addition of the latter. If poured on too rapidly there is considerable danger of the mixture being ejected from the vessel and scattered about, and as the acid is exceedingly corrosive, it is impossible to take too much precaution when adding the water. In ordinary cases where the acid and water are to be mixed, it is by far the safer plan to add the acid to the water, as the former will then find plenty of the latter to satisfy its almost insatiable thirst.

When the solution of the crystals is completed, and when the liquid has cooled down to the ordinary temperature, it is ready for use. On completing the circuit and allowing the current to flow, the zinc is dissolved, forming zinc sulphate, and the chromic

acid is converted into chromic sulphate, water being liberated The reaction may be expressed by the equation:

$$\underset{\text{Zinc.}}{3Zn} + \underset{\text{Sulphuric acid.}}{6H_2SO_4} + \underset{\text{Chromic acid.}}{2H_2CrO_4} = \underset{\text{Zinc sulphate.}}{3ZnSO_4} + \underset{\text{Water.}}{8OH_2} + \underset{\text{Chromic sulphate.}}{Cr_23(SO_4)}$$

This cell has an electro-motive force of about 2 volts, while its resistance is very low. It can yield, therefore, a considerable current, which does not, however, last long, rarely more than an hour or so, the cell then becoming polarised. On the other hand, when only used occasionally, the same solution will last for a long time. As there is a tendency, by secondary chemical reactions taking place between the various constituents of the cell, to form hard crystals of a double salt (known as chrome·alum), which at times cause a fracture of the jar, it is advisable to avoid square or flat vessels for this cell. As we shall presently see, a modification is extensively used on account of its high electro-motive force, its low internal resistance, and its approximation to constancy.

We come now to consider the double-liquid cells, the great aim of which is to obtain constancy, even if at the cost of a higher internal resistance. The chief obstacle to constancy, we have seen, is the accumulation of hydrogen on the negative surface and the consequent polarisation of the cell. Daniell overcame this by using a metallic salt in the neighbourhood of the negative plate, separated from the zinc solution by means of a porous division. The liquid in the copper division contains a large quantity of the same metal as that of which the plate itself is constructed, and it is due in a great measure to this fact that the Daniell cell is very constant. The cell is put together in a great variety of shapes and patterns, varying with the purpose to which it is intended to be applied. It consists essentially of an outer porcelain or other non-porous vessel, containing the zinc. Inside this is placed an unglazed earthenware vessel, which contains a piece of thin sheet copper. The porous vessel is nearly filled with crystals of copper sulphate (known more generally as bluestone), and water is poured on till the copper plate is nearly covered.

If the cell is not required for immediate use, water only is placed in the outer division with the zinc plate. The copper sulphate crystals readily dissolve, and in the course of a day or so

a small quantity of the solution will have passed through the porous partition into the zinc division. The sulphate at once enters into action with the zinc plate and forms sulphate of zinc, which enters into the solution. This action is represented by the equation :

$$\underset{\text{Zinc.}}{Zn} + \underset{\text{Copper sulphate.}}{SO_4Cu} = \underset{\text{Zinc sulphate.}}{ZnSO_4} + \underset{\text{Copper.}}{Cu}$$

The copper thus liberated is deposited in a loose or spongy form either upon the zinc plate or at the bottom of the cell. Obviously this is a disadvantage.

On joining up, the zinc sulphate attacks the metallic zinc, fresh particles or molecules of the salt are formed, and metallic zinc is liberated. The liberated zinc decomposes the copper sulphate, forming more zinc sulphate and liberating the copper. Eventually, copper is deposited on the copper plate, the reactions being set forth in the equation :

$$\underset{\text{Zinc.}}{Zn} + \underset{\text{Zinc sulphate.}}{SO_4Zn} + \underset{\text{Copper sulphate.}}{SO_4Cu} = \underset{\text{Zinc sulphate.}}{2ZnSO_4} + \underset{\text{Copper.}}{Cu}$$

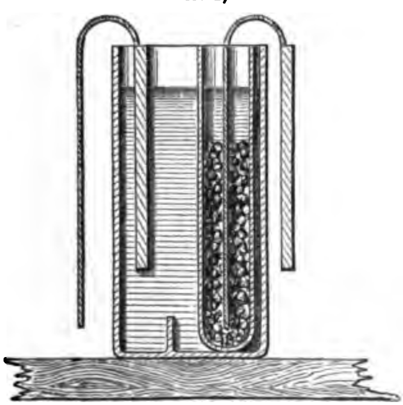
A little study will reveal to the student something of the greatness of the advance thus made. In the first place, we find that instead of the deposition of a hydrogen film on the copper plate, copper, purer than can be obtained by any other simple process, is deposited. We see also that for every atom of zinc dissolved one atom of copper is deposited, and for every molecule of copper sulphate decomposed one molecule of zinc sulphate is formed. Theoretically, then, the gross quantity of zinc sulphate should be continuously increasing, while the copper sulphate should diminish in precisely the same ratio—that is, one molecule or equivalent of zinc sulphate should be formed for every molecule or equivalent of copper sulphate that is decomposed. Further, for every sixty-five parts by weight of zinc dissolved sixty-three parts by weight of copper should be deposited.

The chemical changes, however, which are brought about in the Daniell by the propagation of the current constitute only a portion, and that a by no means large one, of the total amount of chemical change that ensues on fitting up the cell. The

porosity of the unglazed earthenware partition, while it allows the two solutions to come into contact, also permits of their continual diffusion or mixing, more particularly when the cell is at rest. The immediate consequence of this is, that the copper sulphate solution which passes through into the zinc division has its copper displaced by zinc, thereby converting the copper sulphate into zinc sulphate. Beyond a certain point all this means so much waste. The deposit on the zinc plate, if allowed to continue, converts the cell, in a great measure, into one with two copper surfaces, whence the electro-motive force falls.

When the battery is intended only for occasional use, or when the external circuit is of relatively high resistance, it is advisable to use somewhat dense porous partitions, whereby the diffusion of the solutions is hindered. The use of denser porous partitions implies, of course, a proportional increase in the internal resistance of the cell. Generally speaking, it is not advisable to employ the Daniell for occasional work on account of the loss due to the interchange of the solutions and the wasteful consumption of the zinc and sulphate of copper.

FIG. 27



If the cell is required for immediate use, the zinc division should be filled with a weak solution of zinc sulphate, instead of with water only, and the copper division with a saturated solution of copper sulphate. Action then commences at once, with the maximum electro-motive force and without any risk of polarisation.

The circular form of battery is extravagant in the matter of shelf or floor space, while the flat type, which has practically superseded the circular ones, is essentially compact, and is for that reason to be preferred. Fig. 27 is a section of one of the flat single-cell porcelain vessels. There is a little ridge along the

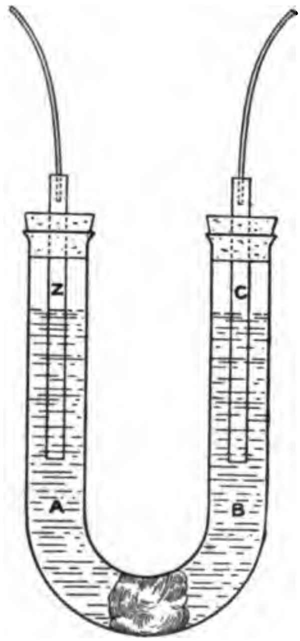
bottom of the cell to keep the flat porous vessel in position. This porous vessel containing the copper plate is filled up with copper sulphate crystals, the zinc plate, which should not be less than $\frac{1}{4}$ inch thick, being suspended in the zinc sulphate solution. For reasons of economy, Daniell cells are frequently made up in teak troughs or boxes, each trough containing a number of cells, say 5 or 10, slate partitions being used to divide the trough into the desired number of cells. The inside of the teak and the slate partitions are then coated with marine glue to render them water-tight. It will be noticed that the copper plate is attached to the zinc of the next adjacent cell. It is usual in practice to rivet one end of a copper strap on to the copper plate, the zinc being cast on to the other end of the strap. In this way expensive binding screws or terminals are dispensed with, and a good and substantial contact is ensured. The last zinc and the last copper are connected to brass terminals, which become respectively the negative and positive poles of the battery.

All porous pots should be dipped, top and bottom, in melted paraffin wax, so as, by filling up the pores, to prevent the solutions mingling too freely or rising to the top above the level of the liquids, and thereby allowing the water to evaporate and the salts to crystallise out. One side of the porous pots may also be paraffined with advantage, viz. the side which is remote from the zinc. A porous pot which has been once used should not be allowed to get dry, as the crystals which form on drying will chip it, and render it useless.

The Daniell cell, when in good condition, can be employed as a fairly reliable standard of electro-motive force, and owing to the ease with which the copper salt is decomposed, the cell possesses one great advantage over the Clark standard cell, in that it does not polarise even when joined on short-circuit for a considerable time, and can consequently be used to give a standard *current* of, say, one milliampere. It has, however, the disadvantage that for accurate measurement it requires a certain amount of attention, which must be particularly directed to the zinc division to keep it free from copper. Such a cell will maintain an electro-motive force of 1·07 to 1·08 volt for a considerable time.

There is a form of standard Daniell which we have found very easy to make and very inexpensive. It consists of a **U**-tube (fig. 28) about half an inch in diameter and 5 inches long in the leg. A little cotton-wool is pushed down to the bottom of the bend to form the porous partition. One leg, B, is provided with a quantity of saturated solution of sulphate of copper, and the other leg, A, with a semi-saturated solution of sulphate of zinc. A piece of pure copper wire, say three-sixteenths of an inch thick, forms the negative plate, the positive plate consisting of a rod of chemically pure zinc, such as can be obtained of any dealer in chemical materials. These rods are fixed in position and the ends of the tube closed by means of corks. The cell can be secured to a wooden stand by means of an indiarubber band, and wires connected to the rods can be joined to terminals fitted on the board. Such a cell can be put together in a few minutes, and always secures a reliable standard of electro-motive force quite good enough for ordinary practical work; but of course its internal resistance is too high to enable it to be used to give a current of such a strength as can be obtained from the ordinary cell made up with fairly large plates.

FIG. 28



The Grove and Bunsen cells are very much alike. Zinc, as usual, constitutes the positive plate in each case, the liquid placed with it being a solution of sulphuric acid in the proportion of 1 part of acid to 7 or 8 parts of water. The negative plate in the case of the Grove cell consists of a sheet of platinum foil, and in the case of the Bunsen of a slab or block of gas-retort carbon; concentrated nitric acid is the depolarising (or hydrogen-absorbing)

liquid which surrounds the negative plate. The Grove cell is usually contained in a flat rectangular porcelain vessel, the zinc plate being bent into a U-shape to embrace the flat porous pot which contains the platinum foil. By this arrangement each surface of the platinum has opposed to it a surface of zinc, the internal resistance being consequently very low.

Zinc sulphate is formed by the action of the sulphuric acid on the zinc, and the hydrogen which is thereby released reduces the nitric acid (HNO_3) to water and nitric peroxide (N_2O_4), which ascends as a gas into the air. This gas is distinguishable from all others by its dense brown appearance and its extremely pungent odour.

The chemical reactions may be represented by the equation:

$$\underset{\text{Zinc.}}{Zn} + \underset{\text{Sulphuric acid.}}{So_4H_2} + \underset{\text{Nitric acid.}}{2HNO_3} = \underset{\text{Zinc sulphate.}}{ZnSO_4} + \underset{\text{Water.}}{2OH_2} + \underset{\text{Nitric peroxide.}}{N_2O_4}$$

The nitric acid, which, to give the maximum strength of current, should be concentrated, is seriously weakened as the current is produced. This results, in the first place, from the fact that every atom of hydrogen set free from the sulphuric acid decomposes a portion of the nitric acid, while, in the second place, the water which is thereby formed dilutes and so weakens the remaining acid. The acid, which, when first poured in, should be quite colourless, is first turned brown by the peroxide (which is more or less soluble in the acid), changing subsequently to green, when it is practically useless.

FIG. 29

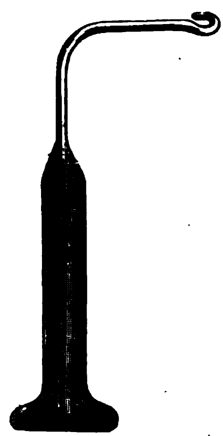
The Bunsen cell, which is illustrated in fig. 29, is most frequently made in a circular form. The outer jar is of glazed earthenware, and contains the solution of sulphuric acid, with a cleft zinc cylinder, and inside this is

placed the porous cell, containing a rod of carbon, immersed in strong nitric acid. The porosity of the carbon enables it to present to the liquid a very extended surface, as compared with the platinum of the Grove cell.

The action of the battery is precisely the same as in the Grove, since the carbon and platinum remain chemically unaffected.

The Daniell and the Grove cells are the representatives of two extensive classes of battery. Daniell's has attained its high standard of popularity on account of its cheapness and its constancy. The Grove, on the other hand, develops a high electromotive force, but, owing to polarisation, it runs down rapidly and is not reliable for more than three to four hours at a time. It was for a long time the typical cell for lecture and demonstration purposes, but the general distribution of electric supply services is rapidly driving it out of use.

FIG. 30

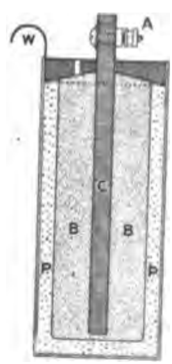


There are many forms of double-fluid bichromate batteries. In nearly all of them zinc and carbon are employed for the positive and negative elements respectively, the difference being, generally speaking, confined to the depolarising solution surrounding the carbon plate. In one of them, however, a feature is made of the means adopted for keeping the zinc well amalgamated or coated with a film of mercury-zinc amalgam, the object of which is to cover up any impurities which may be present in the zinc and to offer a uniform surface to the solution. This cell is known as the 'Fuller,' and it is usually made up in a round earthenware jar, in which is placed a com paratively small porous pot containing the zinc rod, which is of a peculiar shape, as shown in fig. 30. The zinc is cast on to a stout copper wire which passes almost to the bottom of the rod and helps to keep it intact. Two or three ounces of mercury are placed in the porous pot, which on the addition of the solution (dilute sulphuric acid) creeps up the surface of the zinc by the

force of capillary attraction, and so keeps it uniformly and automatically amalgamated. A plate of gas-retort carbon is placed in the outer vessel in a solution of bichromate of potash, derived from a stiff paste, of which a quantity is placed in the bottom of the cell, and which contains, probably, a quantity of free chromic acid, soda nitrate, &c. An unusually large quantity of this solution is generally provided, in order to maintain its strength for a longer period than would be the case were the more usual proportions adopted. The chemical action is practically the same as that in the single-fluid bichromate cell. The electro-motive force of the cell averages 2 volts, and its internal resistance, which depends largely upon the porosity of the porous pot, should be about 2 ohms.

A distinct type of cell, known as the 'dry' cell, is now in extensive use; but nearly all the forms of this type of cell are in principle modifications of the Leclanché cell, having zinc and carbon for the positive and negative plates, sal-ammoniac to attack the zinc plate, and manganese peroxide to intercept the hydrogen. The electro-motive force is therefore in all cases about the same as that of the Leclanché, viz. 1·5 volt. The chief feature in these cells is the absence of any *liquid*, the materials being made up into a damp paste. Were the cell really dry, chemical action could not take place, and no current could be produced. As it is, the cells are liable to become useless as the moisture in the paste evaporates and the internal resistance rises. One of the many forms of dry cell is shown in section in fig. 31. It is contained in either a circular or a rectangular zinc vessel, which is at the same time the positive plate, and which is provided with a lining, P, composed of plaster of Paris, flour, chloride of zinc, sal-ammoniac, and water mixed up into a paste, which quickly sets after having been placed in position. Inside this is another paste, B, surrounding the carbon plate, C, and composed of carbon, peroxide of manganese, chloride of zinc, and water. The chloride of zinc,

FIG. 31



which is increased in amount during the action of the cell, is a deliquescent salt, and it therefore assists in keeping the pastes moist. The top of the cell is sealed in with a layer of pitch or other similar material resting on a layer of silicated cotton. A small hole through the pitch permits the escape of such gases as may be liberated. Connection is made to the carbon by means of a brass terminal screw, A, and to the zinc cylinder by means of a copper wire or strip, W.

When newly made the resistance of the cell is considerably less than half an ohm, but it rises steadily as the contents become dry. The resistance can, however, be lowered again, although not to its initial value, by the introduction through the vent-hole of a little weak solution of sal-ammoniac. As a rule it is cheaper to replace a high-resistance cell by a new one.

Dry cells are certainly very handy, more particularly for testing operations, where the batteries have to be carried about, as there is no risk of spilling the solution, and the cells are always immediately available.

Primary batteries are of little, if any, service in electric lighting. They are valuable for testing purposes, but as sources of current for the electric light they are altogether out of place, owing to the fact that zinc, which is in every case used as the positive plate, and which, being consumed in the generation of the current, corresponds to the coal consumed in a boiler, is very many times dearer than coal. Even were expense a question of minor importance, there still remains the fact that primary batteries are very troublesome to maintain, and most of them give off noxious fumes, which are also as a rule corrosive.

There are three considerations that have to be taken into account when determining what kind and what number of cells it would be most advisable to employ for any particular purpose: first, the relative constancy; secondly, the electro-motive force; and, thirdly, the ratio between the internal resistance of the cell and the external resistance (or the resistance of the connecting wires and apparatus). It will have been gathered that there is in the matter of electro-motive force and constancy considerable variation. We will not enter here into the question of expense, for in the end that which is the best cell for any particular purpose

generally proves to be also the cheapest. The internal resistance is, however, an important factor. If it were negligible, it would, for example, be possible to maintain a current of one ampere by one Daniell cell having an electro-motive force of, say, one volt working through an external resistance of one ohm; for as

$$C = \frac{E}{R}, \text{ then } \frac{1 \text{ volt}}{1 \text{ ohm}} = 1 \text{ ampere.}$$

But the average Daniell cell offers 4 ohms resistance, so that the current, where R is the external resistance of 1 ohm, and r the internal resistance, would be

$$\frac{E}{R + r} = \frac{1}{1 + 4} = \cdot 2 \text{ ampere};$$

and if we were to attempt to increase this current materially by the addition of, say, nine other similar cells, we should fail, for then

$$\frac{10E}{R + 10r} = \frac{10}{1 + 40} = \cdot 25 \text{ ampere nearly.}$$

Similarly, with 100 such cells through this unit resistance—

$$\frac{100E}{R + 100r} = \frac{100}{1 + 400} = \cdot 25 \text{ ampere nearly.}$$

We see, then, that increasing the number of cells in this way, when the external in comparison with the internal resistance is low, produces no correspondingly good effect, for the simple reason that, although we proportionally increase the electro-motive force by so doing, we at nearly the same rate increase the circuit resistance. As a matter of fact, no Daniell cell or battery, unless made of abnormal dimensions, can possibly develop a current of 1 ampere, its internal resistance being too high.

On the other hand, were we to employ Grove cells (which, for the sake of simplicity, we will assume to have an electro-motive force of 2 volts per cell), the advantage of increasing the number of cells on a low resistance circuit soon becomes apparent. For example, with an external resistance of 1 ohm and an internal resistance of ·2 ohm per cell, one cell would give us

$$\frac{E}{R + r} = \frac{2}{1 + \cdot 2} = 1 \cdot 6 \text{ ampere.}$$

Two such cells would produce

$$\frac{2E}{R + 2r} = \frac{4}{1 + \cdot 4} = 2\cdot 85 \text{ amperes;}$$

and three cells

$$\frac{3E}{R + 3r} = \frac{6}{1 + \cdot 6} = 3\cdot 8 \text{ amperes nearly.}$$

Similarly, four cells would give 4·4 amperes, and five cells would yield 5·0 amperes. But from ten cells we should only get

$$\frac{10E}{R + 10r} = \frac{20}{1 + 2} = 6\cdot\dot{6} \text{ amperes.}$$

While with 100 such cells the current would be

$$\frac{100E}{R + 100r} = \frac{200}{1 + 20} = 9\cdot 5 \text{ amperes,}$$

showing again that as the internal resistance approaches or exceeds the external the proportional increase of the current is lessened. When, however, the external resistance is relatively high, say 1000 ohms, the battery resistance becomes proportionally low, and, therefore, to a corresponding extent, negligible. The current from one Daniell cell would be

$$C = \frac{E}{R + r} = \frac{1}{1000 + 4} = \cdot 000996 \text{ ampere.}$$

With ten cells we should get

$$\frac{10E}{R + 10r} = \frac{10}{1000 + 40} = \cdot 00961 \text{ ampere,}$$

or, practically, a current of tenfold strength.

Similarly, with a battery of 100 cells we should get

$$\frac{100E}{R + 100r} = \frac{100}{1000 + 400} = \cdot 0714 \text{ ampere.}$$

Again, one Grove cell would give through 1000 ohms

$$C = \frac{E}{R + r} = \frac{2}{1000 + \cdot 2} = \cdot 002 \text{ ampere,}$$

and ten cells would give

$$\frac{10E}{R + 10r} = \frac{20}{1000 + 2} = 0199 \text{ ampere.}$$

From 100 cells we should get

$$\frac{100E}{R + 100r} = \frac{200}{1000 + 20} = \cdot 196 \text{ ampere.}$$

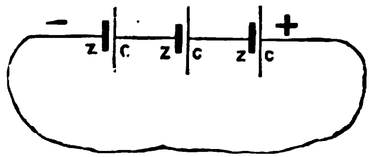
With either the Daniell or the Grove the strength of the current increases in almost the same ratio as the number of cells when the external resistance is high. But as the Grove is vastly inferior to the Daniell in constancy, and as it is a very expensive form of battery, the deduction is that Daniell cells should be used for circuits of high resistance, compensating for their lower electromotive force by a corresponding increase in numbers. On the other hand, the Grove, in consequence of its low internal resistance, is better adapted for circuits of low resistance, such as are frequently met with in experimental work.

The internal resistance of different cells of any particular type varies inversely as the size of the plates (counting only the active or opposed surfaces). It also varies directly as the distance between them (making due allowance for the resistance of the porous pot, which would, of course, have a constant value unless varied in material or dimensions). The meaning of this is plain, for if we were to double the size of the plates we should halve the resistance and proportionally increase the current strength.

The same object is attained by joining cells in 'parallel.' So far we have only considered them as joined in series—that is to say, the copper of one cell joined to the zinc of the next, and so on. Under such circumstances the electro-motive force of the battery is equal to the sum of the electro-motive forces of the individual cells. If the coppers of two cells are joined together, and likewise the zincs, and the two junction wires connected to the external circuit, a current will be developed by an electromotive force equal to that of one cell, the joint resistance of the two equal cells being half that of one of them used separately. The arrangement is, in fact, equivalent to doubling the size of the plates of a single cell.

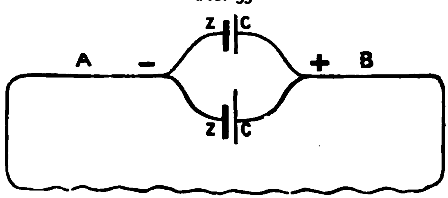
This will, perhaps, be made clearer by a reference to the diagrams, figs. 32, 33, and 34. Fig. 32 represents a battery of

FIG. 32



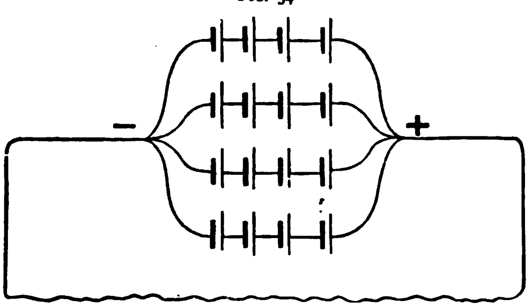
three cells joined in series, the short thick strokes representing the zinc or positive plates, and the long thin ones the copper or nega-

FIG. 33



tive plates. Fig. 33 shows two cells joined in parallel. If they are both of exactly the same electro-motive force, no current can

FIG. 34



flow from C to C or from Z to Z, but on joining the external wires A and B together, a current would be generated by each cell and pass through the external circuit from B to A. As already stated, the joint resistance of these two cells would be half that of one

of them, and with a low external resistance the current strength would be increased proportionally. In fig. 34 are shown sixteen cells divided into four sets of four cells each, the sets being joined up in parallel. On completing the external circuit a current will flow, due to an electro-motive force equal to that of four cells, but the battery resistance will be only one-fourth of that of four cells.

The joint resistance of any number of parallel batteries is equal to $\frac{rs}{B}$, where r is the resistance per cell, s the number of such cells joined up in series in each individual battery, and B the number of such batteries joined together in parallel. This is simply an application of the law that with a number of conductors, N, of uniform resistance, R, joined together in parallel, their joint resistance is equal to $\frac{R}{N}$, for rs is the total resistance of each of the batteries joined together in parallel. This arrangement is sometimes very advantageous; for example, if sixteen Daniell cells, each of 1 volt electro-motive force and 4 ohms internal resistance, are employed in series for a circuit of 4 ohms external resistance, the current will be

$$\frac{16}{4 + 64} = \cdot 235 \text{ ampere} \quad . \quad . \quad (1).$$

By dividing the cells into two sets of eight cells each and joining these in parallel the current is increased, thus:

$$\frac{8}{4 + 16} = \cdot 400 \text{ ampere} \quad . \quad . \quad (2).$$

On rearranging the cells, as shown in fig. 34, the current becomes

$$\frac{4}{4 + 4} = \cdot 500 \text{ ampere} \quad . \quad . \quad (3).$$

Pursuing this plan any further, however, results in a diminution of the current, because the gain in reduced resistance is overbalanced by the loss in electro-motive force; for example, if eight sets of two cells each are joined in parallel, we get

$$\frac{2}{4 + 1} = \cdot 400 \text{ ampere} \quad . \quad . \quad (4).$$

While with the whole of the sixteen cells joined in parallel we get only

$$\frac{1}{4 + \cdot 25} = \cdot 235 \text{ ampere} \quad . \quad . \quad (5).$$

With circuits of comparatively low external resistance there is, therefore, a best possible arrangement of the cells to give the strongest possible current, and with any given number of cells this arrangement is arrived at when the internal resistance is equal to the external resistance, or when $R = \frac{rs}{B}$.

Such an arrangement is not, however, economical; nor indeed is any arrangement, unless the external resistance is considerably in excess of the internal.

As has been already stated, the strength of the current is the same in all parts of the circuit; consequently in (1) sixteen times as much zinc, &c., is consumed in the sixteen cells as is consumed in any one of them. In (3), however, each set of four cells must be considered as a separate or branch circuit, and only one-fourth of the current flowing in the external circuit would flow through each of these separate sets. The external current is approximately twice as strong as in (1). Therefore the individual current in each cell and the consequent consumption of zinc is only half as great. In (5), where there are sixteen cells in parallel, a current is produced equal to that resulting from a battery of sixteen cells in series, but, the cells being joined up in parallel, only one-sixteenth of this current flows through each cell, so that the total consumption of zinc in the sixteen cells is but equal to that in a single cell in (1), clearly demonstrating the advantage, from an economical point of view, of using batteries much lower in resistance than the wire and apparatus through which the current has to flow.

One important feature concerning the proportion between the electro-motive force of the battery and the difference of potential it can maintain in any given external circuit requires careful consideration. It was pointed out in Chapter II. that in any given circuit the fall of potential varies directly as the resistance, so that in (1), where the internal bears to the external resistance the proportion of 16 to 1, only one-seventeenth of the 16 volts

developed by the battery is available in the external circuit, the remaining sixteen-seventeenths being absorbed in overcoming the resistance of the battery. In (3), the resistance outside the battery being equal to that inside, the electro-motive force of 4 volts developed is halved, 2 volts being available for the external circuit. Similarly in (5) the available electro-motive force for the external circuit is sixteen-seventeenths of a volt (the gross electro-motive force developed being 1 volt), or equal to that produced by the sixteen cells joined up in series, as in (1), where, as already shown, the consumption of materials is sixteen times as great; and, speaking generally, we may say that

$$P = E \frac{R}{R + r},$$

where E is the electro-motive force developed by the battery, R is the external resistance, r is the internal resistance, and P the available potential difference at the terminals of the battery. For example, with a battery, as in (4), whose internal resistance is 1 ohm working through an external resistance of 4 ohms, and having an electro-motive force of two volts, the available potential difference will be

$$P = 2 \frac{4}{4 + 1} = 1 \cdot 6 \text{ volt.}$$

The available potential difference can also be ascertained in another way which does not involve the necessity for ascertaining the external resistance. Ohm's law declares $C = \frac{E}{R}$, or, $E = C R$ And this is true either of a complete circuit or simply of a part of a circuit. If, for instance, in a circuit of known or of unknown total resistance the current strength is found to be, say, 1·5 ampere, and that any portion of the circuit offers a resistance of 3 ohms, then the fall of potential, or the electro-motive force absorbed, e, in that portion of the circuit will be

$$e = Cr = 1 \cdot 5 \times 3 = 4 \cdot 5 \text{ volts.}$$

If the known resistance is that of the battery (r), it follows that 4·5 volts will be the electro-motive force absorbed by the battery, and if that is deducted from the total electro-motive force developed

(say 20 volts), the remainder will be the available potential difference for the external circuit, or

$$P = E - Cr = 20 - (1 \cdot 5 \times 3) = 15 \cdot 5 \text{ volts.}$$

Occasion sometimes arises for substituting one form of battery for another without making any appreciable change in the current strength. If the internal resistance were negligible, this would, of course, be a matter of no difficulty; but even when it is requisite to make allowance for the battery resistance, a simple formula can be employed to ascertain the number of cells necessary to develop a given current strength. For example, suppose that a battery of 100 cells, with an electro-motive force of 1 volt and an internal resistance of 4 ohms per cell, sends a current through an external resistance of 400 ohms, then that current will be

$$\frac{1}{100r + R} = \frac{100}{400 + 400} = \cdot 125 \text{ ampere.}$$

Substituting some other form of battery with an electro-motive force of 2 volts and an internal resistance of 1 ohm per cell, and letting n be the number of such cells necessary to develop 0·125 ampere, then

$$\frac{n \times 2}{(n \times 1) + 400} = \cdot 125 = \frac{1}{8} \text{ ampere;}$$

that is to say,

$$\frac{2n}{n + 400} = \frac{1}{8},$$

or,

$$16n = n + 400$$

$$15n = 400$$

$$\therefore \quad n = \frac{400}{15} = 26 \cdot 6.$$

Twenty-seven of those 2-volt cells would maintain in the circuit a current of

$$\frac{27E}{27r + 400} = \frac{54}{27 + 400} = \cdot 126 \text{ ampere.}$$

Twenty-six cells would be insufficient for the purpose. This formula also possesses the advantage of providing the same poten-

tial difference at the terminals of the battery, as well as that of furnishing the number of cells necessary to develop an equally strong current, for obviously, with a given resistance and a definite current to maintain, a correspondingly definite potential difference must be provided.

The student should make every effort to master these simple calculations and the principles involved, and he will then be in a position to readily understand almost any similar problem which may present itself in connection with dynamo machines and the complex circuits upon which they are usually employed.

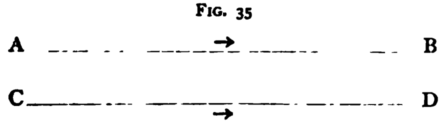
CHAPTER IV

MEASUREMENT OF CURRENT STRENGTH

Having in the preceding chapters shown how a current of electricity can be generated and maintained, and having also explained the various units by which we can measure that current, as well as the resistance, and the pressure or electro-motive force which maintains the current, it behoves us now to turn our attention to the methods of making such measurements, and to the consideration of the laws involved. In order to make the student's progress at this difficult stage as easy as possible we will approach the subject experimentally.

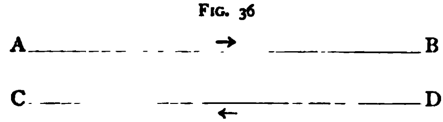
If a wire, A B (fig. 35), carrying a current is brought near another wire, C D, also carrying a current, it is found that there is

Fig. 35



a decided action between the two wires. If the currents are flowing in the same direction, as shown by the arrow-heads in fig. 35, the wires are attracted one to the other. On the other hand, if the currents travel in opposite directions, as in fig. 36, repulsion ensues.

Fig. 36

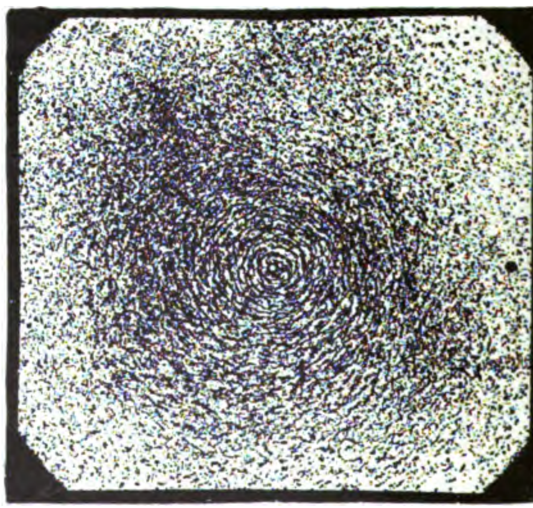


The force of this attraction or repulsion depends, among other considerations, upon the strength of the current. It would be

possible, therefore, to take advantage of this effect, as affording a means of estimating or measuring current strength, and a device for so doing will be described presently.

Now it is impossible for any such action to take place between the two wires without the aid of some intervening medium to transmit the force. This medium is the same as that which transmits the electrical stresses in the other or static state of electricity

FIG. 37



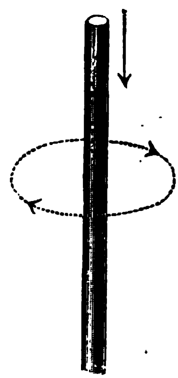
that state in which a body affected by it is said to be electrified or charged with electricity, and is, in all probability, the light carrying ether.

Although it is difficult to understand the precise action in the case now under consideration, it is easy to show experimentally the direction in which the force acts. If we thread a wire through a piece of cardboard, send a strong current through the wire, and then sprinkle iron filings on the cardboard, the filings will arrange themselves in concentric circles round the wire as shown in fig. 37. This arrangement is caused solely by the current, and may be observed at any part of the wire. The lines thus marked out,

which show the direction in which the force due to the current acts upon the filings, are called 'lines of force.'

As in the case of the imaginary lines considered in Chapter I. it is convenient to assume for these lines also a certain direction. That direction along a line of force, indicated by the arrow-heads in fig. 38, is called the 'positive' direction. The direction can be impressed upon the memory by thinking of the act of using a corkscrew. If the longitudinal direction in which the screw moves, either *into* or *out of* the cork, be taken to represent the direction of the current, then the positive direction of the lines of force will be that in which the handle rotates, so that if in fig. 38 the downward direction of the current were reversed, the positive direction of the lines of force would be in the opposite direction to that indicated by the arrow-heads. The space around the wire in which the effect of the current is perceptible is called an 'electro-magnetic field,' and it is important to remember that the strength of this field is exactly proportional to the strength of the current producing it. It extends from the axis of the wire as a centre throughout the surrounding space, but as the distance from the wire increases the effect is weakened, until it at last becomes so feeble as to be imperceptible. The lines of force traversing this field obey similar laws to those laid down for the lines due to a static charge, and the interaction between two sets of lines of force can always be predicted by remembering that their universal tendency is to coincide in direction and to shorten themselves.

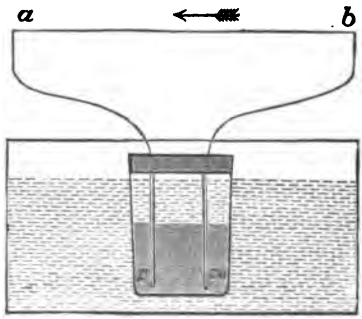
FIG. 38



Reverting to the experiment with the two wires carrying the currents, it may be said that the force exerted between them always tends to move them so that they shall take up such a position that the currents flow in the same common direction (as in fig. 35), and that the wires as nearly as possible coincide. To prove this it is necessary to allow at least one of the wires to be capable of moving freely and with as little restraint or friction as possible. This can be done by means of a simple device for constructing a

movable or floating battery cell. Let a cork be fitted to a small glass beaker partly filled with dilute sulphuric acid, and through the cork pass wires carrying thin strips of zinc and copper, completing the circuit externally by means of a stiff but not too heavy piece of wire, as shown in fig. 39. The small beaker cell can then be placed in a larger beaker, or any other convenient vessel containing water; and, unless too much acid solution has been placed in the smaller beaker or the solid portions are made unnecessarily heavy, the cell will float upon the water. If a wire carrying a strong current is placed parallel to the straight part of the wire, *a b*, so that the currents flow in opposite directions, the wire *a b* will be repelled, and, the cell floating away, will turn completely round, so that the currents in the two wires flow in the same direction; the cell will then be attracted until *a b* lies as near as possible to the other wire.

FIG. 3

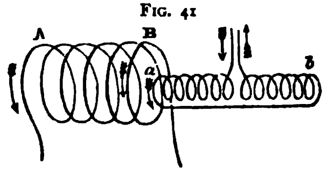


These effects of attraction and repulsion may be increased by increasing the length of the wires, because then a greater number of lines of force are brought into play, but very long straight wires would be cumbersome and, in fact, impracticable. It is, therefore, more convenient to coil them up into flat spirals (fig. 40), covering the wire with silk, cotton, or other insulating material, to prevent adjacent convolutions getting into contact. The effects between the spirals will be similar to those between the same two wires straightened out—that is to say, attraction or repulsion will ensue according to the direction of the currents. For many purposes, however, it is preferable to coil the wire into a long spiral or helix. In fig. 41 one of the helices, A B,

FIG. 40

is floated in a manner similar to that adopted in fig. 39, the other helix, *a b*, being placed near it. The action between two such helices is very decided, and, being of exactly the same character as that between the straight wires or flat spirals, may be predicted by remembering the laws we have just stated. If the currents are flowing in opposite directions round adjacent ends of the spirals or helices, repulsion will take place, and the floating helix, moving more easily than the other, will recede, and, turning completely round on its vertical axis, will approach with its opposite end to the fixed spiral, as in fig. 41. The currents will then be flowing in the same direction, and the floating helix, being comparatively large and its movements not restricted, will not come to rest until it has threaded itself on to or over the other spiral. Such a spiral or helix of wire acts as if the force resided at its extremities (which are termed 'poles'), and this form of spiral is frequently called a solenoid.

FIG. 41



Now the strength of an electro-magnetic field may be measured by the density of its lines of force or the number contained in a given area. From the experiment illustrated in fig. 37 it is clear that the lines are much denser near the wire than at a distance from it. This is also the case when the wire is coiled up into a helix. The greater part of the lines there form little circles, closely embracing the wire from which they are generated, and comparatively few of these circular lines of force pass through the space at the ends or poles of the solenoid, where, if we consider the action of the helix as a whole, the force, generally speaking, appears to be concentrated. It will be evident that if we can by any means divert the circular lines of force so as to compel more of them to pass through the ends of the solenoid, then its effective strength will be greatly increased.

Experiment has demonstrated that iron offers a far easier path for these lines of force than the air does—so much easier, in fact, that they will alter their circular shape and extend a considerable distance from their respective portions of the wire in order to pass

through a piece of iron. Fig. 42 illustrates the distribution of the lines of force in the neighbourhood of a wire carrying a current and surrounded by air; and the manner in which these lines of force may be diverted by placing a piece of iron near the wire is shown in fig 43. The judicious use of iron, then, affords us a ready means of leading the lines to, and concentrating them at, almost any point we please. It may be mentioned that the relative facility with which the lines of force can be transmitted through good soft iron, or the electro-magnetic conductivity of the iron as compared with that of air, may under exceptional circumstances be as high as 2000 to 1.

If, then, we place a bar of iron inside a solenoid, a large percentage of the lines of force lose their circular form, and, passing through this iron 'core' (as it is called), they leave it at its ends

FIG. 42

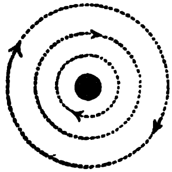
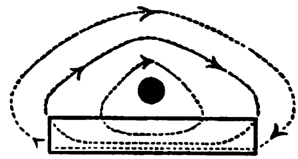


FIG. 43

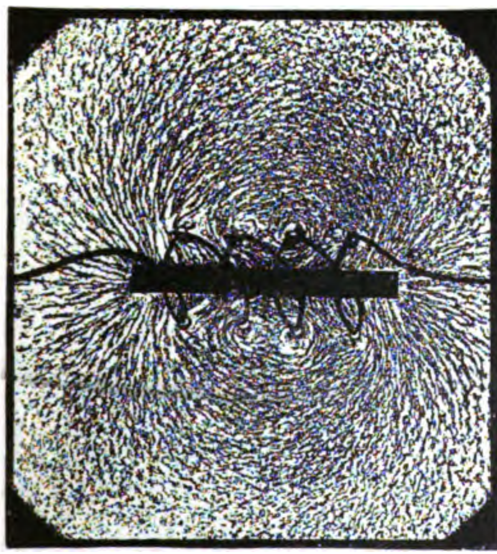


to complete their excursion round the wire from which they were generated. An example of this action of iron is shown in fig. 44, which illustrates the field developed by a powerful current travelling through a solenoid of a few turns, having a core of comparatively small dimensions. Were a larger and more massive core to be introduced, even more of the lines of force would extend themselves through the iron instead of circulating it in the immediate vicinity of the wire.

By the introduction of these iron cores the strength of the action between two solenoids is enormously increased; and a still further increase can be obtained by so shaping the iron that the greatest possible facilities are offered for the lines of force set up by the one solenoid to traverse the space occupied by the majority of those due to the other. The designing of the shape and dimensions of an iron core often becomes an extremely important matter, as, for example, in the case of the dynamo-electric

machines hereafter to be described, in which it is necessary to concentrate an exceedingly powerful field in such a manner that it shall be approximately uniform over a comparatively large space. In such cases the iron cores may be more than a ton in weight, and they are not only expensive to construct, but a considerable expenditure of energy is also required to keep them magnetised. There is, therefore, great scope for effecting economy by making the design such that the cores may be cheaply con-

FIG. 44



structed and yet act efficiently. The student will do well in such cases to always endeavour to think of the iron as simply affording a means of diverting the lines of force set up by the current into just that part of the field where they are required to act. The precise effect on the iron itself is, to a great extent, still a matter for speculation, but it must be remembered that the only way of actually increasing the number of the lines of force setting up the field is by either increasing the current itself, or by increasing

the length of the wire and adding to the electro-motive force sufficiently to maintain the same current strength.

The amount of attraction or repulsion exhibited by the solenoids furnished with their iron cores might be used as a means of measuring current strength; but the arrangement is not a convenient one, owing chiefly to the difficulty in obtaining perfect freedom of motion, the liability of variation in the current strength, and the varying properties of the iron.

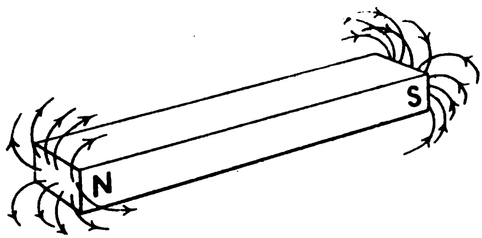
Were it not for these disadvantages we could keep the electro-magnetic force of one of the solenoids constant, and send the various currents to be compared and measured through the other. But here Nature comes in to aid us, for it is found that if a piece of *hard* iron or steel is used as a core for the solenoid, it retains more or less permanently a large portion of the electro-magnetic properties originally produced by the current. The power or ability of retaining such effects or properties is known as the 'retentivity' of the iron or steel, and depends entirely upon its chemical composition and its mechanical or molecular structure. This retentivity is the same property as that frequently but erroneously called 'coercive force.' If retentivity corresponds to anything at all, it is to *inertia* rather than to anything that can fairly be described as coercive. The similarity to mechanical inertia is seen in the fact that those samples of iron which transmit the lines of force freely, *retain* scarcely any of the influences producible by them, while, on the other hand, hard iron and steel, which resist the propagation of the lines of force, also resist the vanishing of these lines after the cessation of the current which called them into existence.

A piece of iron or steel which acquires and so retains the power of acting as a solenoid is called a permanent magnet, or simply a magnet, and its extremities are also called poles. The lines of force still enter and leave the steel as they did before it was removed from the helix, the direction being shown by the arrows in fig. 45. The end, s, at which they are assumed to enter is called the south-seeking pole of the magnet, and the other its north-seeking pole.

The actual arrangement imparted to iron filings sprinkled on a sheet of paper placed over a permanent steel magnet is beautifully

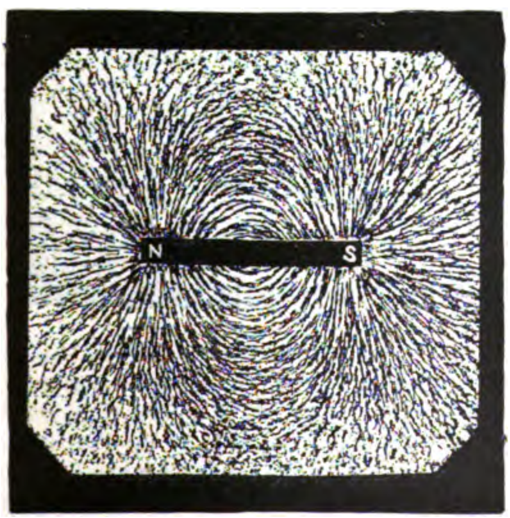
illustrated in fig. 46. It is very similar to the arrangement illustrated in fig. 44, the essential difference being that the

FIG. 45



subsidiary lines or curves surrounding the wire itself are missing, and the field is in consequence much simpler and more clearly

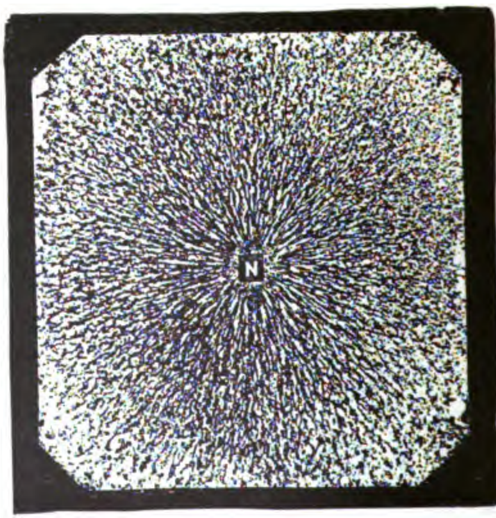
FIG. 46



defined. Such a distribution of the filings as that illustrated in fig. 46 would take place in any plane parallel to the axis of the magnet, for the lines of force radiate from the poles similarly in

all directions. The distribution observed when the paper is placed on the end of the magnet and at right angles to its axis is shown in fig. 47. Here the filings appear to be radially arranged on a horizontal plane. In the absence of the filings the lines of force are in the form of curves in a series of vertical planes, but as the power of the magnet is inadequate to hold the filings in position in mid air, they are projected vertically downwards, so that the arrangement shown in fig. 46 is just that which

FIG. 47

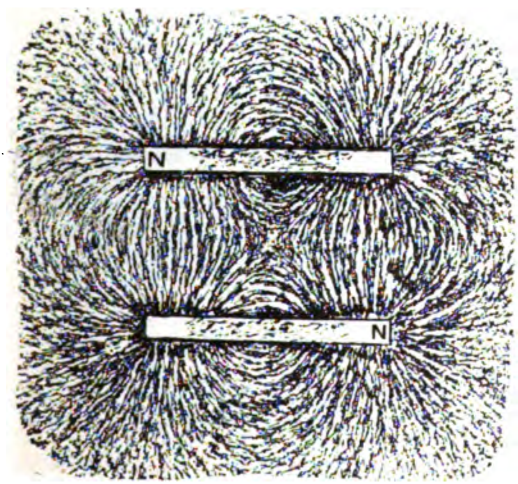


the arched curves would assume were they viewed rom a position immediately over and at some distance from the paper.

It is advisable that the student should have a good idea of the effect produced upon a field of force by the introduction of another field. For example, in fig. 48 two permanent magnets have been used, and the arrangement of the filings between them is very different from that arrangement illustrated in fig. 46. The point to be observed is that the lines of force invariably pass between opposite poles, and in the space between the magnets a line springing, say from one of the north poles, selects the path to

the nearer of the two south poles. The effect of interposing a bar of soft iron placed midway between the magnets is illustrated in fig. 49. Many of the lines of force pass through the iron, the number being about the same from the two magnets. As, however, the two sets of lines of force pass through the iron in opposite directions, no definite polarity is developed in the iron bar, the north polarity at one end due to one magnet being equal to the south polarity at the same end due to the other magnet. The student is advised to experiment with a pair of magnets and

FIG. 48

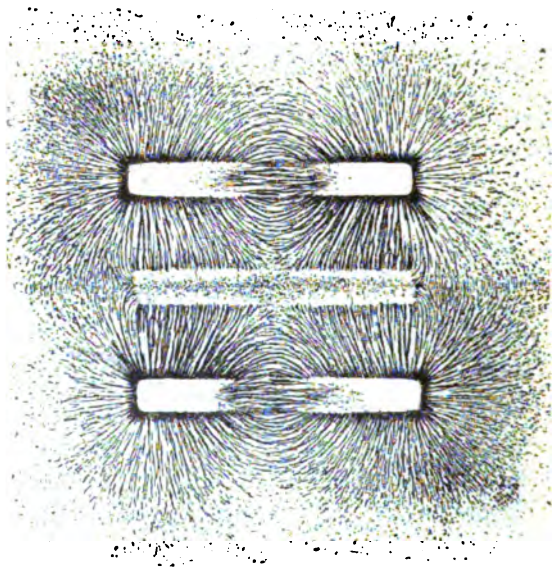


a number of iron bars of various dimensions, arranging them in as many different ways as possible. The iron filings sprinkled over the several combinations will enable him to study with considerable interest the alteration in the fields as he varies the relative positions of his magnets and iron bars.

If we know the direction in which the current passes round a piece of iron or steel, it is easy to predict the direction of its polarity or the direction of its magnetisation, for if we look at the end of the bar, and the current is then flowing round it in a right-handed direction, as in fig. 50, that end will be a

south-seeking pole; but if the current flow in a left-handed direction, as in fig. 51, that end will be a north-seeking pole.

FIG. 49



It is the practice to enter into a detailed description of the difference between right- and left-handed helices, with a view to

FIG. 50

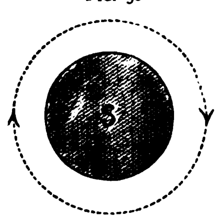
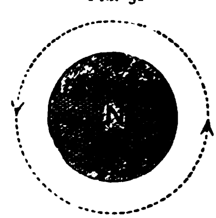


FIG. 51



facilitating a recollection of the electro-magnetic polarity. Thus a left-handed helix (fig. 52) is one in which, from whichever end the current enters, it will travel in the opposite direction to that

taken by the hands of a clock, and will develop north-seeking polarity at the end at which it enters and south-seeking polarity at the end of emergence. Conversely, a right-handed helix (fig. 53) is one in which the current will travel round in the same direction as the clock-hands. In this the entering end becomes a south pole and the other end a north pole. But all this is super-

FIG. 52

fluous. It is sufficient to regard the cause and effect in the way indicated in the preceding paragraph.

It is noteworthy that two magnets act one upon the other in precisely the same manner as two helices or a helix and a magnet, for in every case the movement or motion imparted is such as

FIG. 53

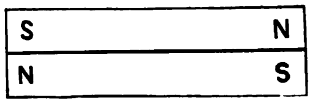
will tend to make the lines of force coincide in direction. Thus, if one magnet, A (fig. 54), is brought near another, B, which is suspended by a thread or pivoted on a needle-point as at C, so that it can turn freely about its centre, the force exerted between them will endeavour to make the suspended magnet take up

FIG. 54

such a position as to allow the lines of force due to both magnets to pass through them in the same direction. This will happen when the magnets are in line and when their opposite poles are adjacent, as shown in fig. 54. In other words, there will be repulsion between similar magnetic poles and attraction between dissimilar ones.

If, however, both magnets are allowed perfect freedom of motion, their ultimate position will be similar to that shown in fig. 55, the magnets then lying side by side with their dissimilar poles adjacent. In this position the coincidence of the lines of force is at a maximum: that is, the lines due to each magnet turn round at the ends and pass through the other, and in so doing assume the easiest path for their completion. If pieces of soft iron, called armatures or keepers, were placed across the extremities of the magnets, the circuit of the lines of force would be continued through them to such an extent that few or none of the lines would traverse the air.

FIG. 55



These armatures are, however, rarely made properly, their mass being far too small, and their shape far from the best possible; but this point we will deal with more fully in Chapter VII.

The strength of a magnet pole can be estimated by measuring the force with which it attracts or repels another pole, the force being equal to the product of the two polar strengths; or, if M represents the strength of one pole, and M_1 the strength of the other similarly magnetised, the force of their repulsion will be $M \times M_1$. This force of repulsion is not, however, the same at all distances, but varies inversely as the square of the distance; so that we might express the force *f*, between two magnet poles, by the simple formula

$$f = \frac{M \times M_1}{d^2}$$

where *d* equals the distance in centimetres between the poles. Since we cannot possibly obtain a single isolated pole, it is, when endeavouring to verify this statement by experiment, important to bear in mind that the distance between the two poles of each magnet should be as great as possible—or, in other words, that the magnet should be as long as possible—to minimise the error that would be produced by the ever-present tendency of the remote poles to act oppositely to the adjacent ones.

We have already defined the dyne as the unit of force, and the magnet pole of unit strength is such a one that if placed at a dis-

tance of one centimetre from a similar and equal pole it will repel it with a force of one dyne. Consequently, the strength at any point in any field can be determined by measuring in dynes the repulsion at that point of a magnet pole of unit strength. In every case, then, the force acting upon a magnet pole is found by multiplying the strength of the pole by the strength or intensity of the field in which it is placed. In order to numerically compare the strengths of magnetic fields by the relative densities of the lines of force, it is assumed that a field of unit strength contains one line of force per square centimetre.

The earth itself is practically a huge misshapen or irregular magnet, and behaves as such, acting as if its poles were situated relatively near, but actually at some distance from, the geographical poles. If a magnet needle were suspended so that it could turn freely in a *vertical* plane, it would, with a plane of rotation east and west, point with its north pole vertically downwards; but if the plane of rotation were north and south, the needle would, in London, come to rest with the north-seeking pole dipping downwards, and making an angle—known as the angle of inclination or dip—of about 67° with the horizon. If a second magnetic needle were suspended or balanced on a pivot in a *horizontal* plane, it would set itself approximately north and south, the north-seeking pole pointing to the north magnetic pole of the earth. The axis of the magnet—that is, the straight line joining its two poles—would actually make an angle—known as the angle of declination—of about 16°, with the geographical meridian passing through its centre.

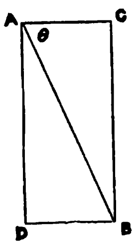
It will be observed that there is here a case of attraction between the north pole of the earth and the north-seeking pole of the magnet; but this is no contradiction of the law that similar poles repel and dissimilar attract, inasmuch as the magnetic properties of the north pole of the earth are in all respects the same as those of the south-seeking pole of a magnet.

The earth's *total* magnetic force as observed at any point in the northern hemisphere can be resolved into two components at right angles to each other, one acting in a vertical direction, tending to depress the north-seeking pole of the needle, the other acting in a horizontal direction and striving to make

H 2

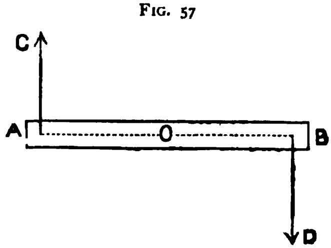
the needle point north and south. Their relative values may be found by the familiar parallelogram of forces (see fig. 56) The line A B is drawn making an angle θ with the horizontal equal to the angle of inclination, and the right-angled parallelogram which has A B for a diagonal is then completed with its sides horizontal and vertical. Then, if A B represents in length the magnitude of the total magnetic force, A C and A D will be proportional to the horizontal and vertical components respectively.

FIG. 56



When the magnet is so balanced that it can only move in a horizontal plane, then a large proportion of the force—viz. the vertical component—is simply exerted in pressing the magnet on its support. The remainder, or the horizontal component only, is effective in making the magnet point towards the magnetic north and south. On the other hand, when the plane of a dipping needle is at right angles to the magnetic meridian, or to the direction of the earth's lines of force, the vertical component only is active, and the magnet points vertically downwards, the horizontal component spending its force in pressing the pivots against their bearings, vainly striving to urge the needle round into the direction of the dip. When the plane of such a needle is parallel to the magnetic meridian the total force can then be exerted upon it, urging it to point in the line of dip, the lines of force due to the earth's magnetism being able in that position to coincide exactly with those of the needle. A horizontally balanced magnetic needle is useful in pointing out the direction of the north and south magnetic poles of the earth.

FIG. 57



In consequence of the immensity of the earth as a magnet, its magnetic field is practically uniform over any small space near the surface of the earth—that is, its lines of force throughout any such small space are *parallel* and *equidistant*. It follows, therefore, that the poles of a needle floating on water are attracted

and repelled with equal force in any position, and as a consequence of this the needle does not move bodily towards the north pole of the earth, but is simply directed so as to point north and south.

We may here consider the well-known law in mechanics that when two equal forces, parallel but opposite in direction, act at the ends of a rigid bar, they tend to turn it round upon its centre. The turning effort is greatest when the forces act at right angles to the bar, as do C and D in fig. 57, A B being the rigid bar. The amount of this turning effect M is equal to the sum of each of the two forces multiplied by the distance from the centre; that is,

$$M = (C \times OA) + (D \times OB),$$

whence, C being equal to D,

$$M = C\,(OA + OB),$$

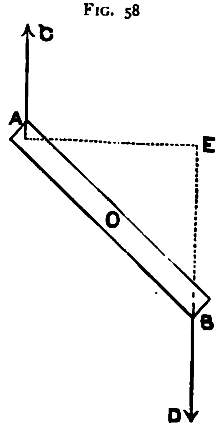
that is,

$$M = C \times AB,$$

or the turning effort is equal to the product of one of the equal forces into the perpendicular distance between them.

Such a pair of equal forces is called a couple, the perpendicular distance between their direction being called the arm of the couple; and the turning effort, M, as measured by the product of one of the forces into the arm, is the moment of the couple. As the bar turns round or rotates, the moment M is decreased, the forces being the same but acting at less advantage—in other words, the *leverage* is reduced. This will be more evident from a consideration of fig. 58, where the perpendicular distance between the directions of the forces is A E, and consequently the moment of the couple is C × A E.

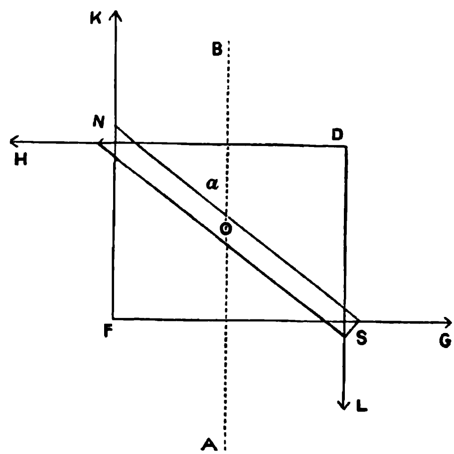
FIG. 58



Reverting once more to the experiment with the floating needle, if we call the strength of one of the poles of the needle *m* and let H represent the horizontal component of the earth's magnetic field, then the force acting on each end of the needle

is $m \times$ H. If we place the needle so as to point east and west, the arm of the couple is equal to the full length l of the needle, whence the moment is $m \times$ H $\times l$. This moment decreases as the needle moves round towards zero, or that position in which it is pointing north and south. The moment is then reduced to nothing, M becoming $m \times$ H $\times$ O, because the length of the arm is nothing; *consequently the needle remains at rest.* The horizontal component only is taken into consideration, because that is the only part of the earth's total magnetic force which is able to act effectively upon the needle and move it in a horizontal plane.

FIG. 59



Now we can cause any current, the strength of which we may desire to measure, to develop a field of strength f at right angles to the earth's directive force—that is to say, we can cause the current to travel north and south, and by so doing deflect a magnetic needle from its zero position, the wire carrying the current being placed either above or below the needle. Then the new force acting on each end or pole of the needle will be $m \times f$, where m is again the strength of the magnet pole; and, the length of the arm being calculated as before, the moment will be $m \times f$ multiplied by that arm. Manifestly, the needle will

come to rest in a position where the moment of the couple due to the current is equal to the moment of the couple due to the earth.

Let the needle N S (fig. 59) be so deflected by a current, and make an angle, N O B, called the angle of deflection, with the magnetic meridian, A B. This angle N O B is, of course, equal to the angle N S D. Let this angle be called $a°$, and let f be the strength of the field due to the current, the direction of the action of which is indicated by the arrows D H and F G. D S is then the perpendicular distance between these directions, whence the moment of the couple due to the current is $m \times f \times$ D S.

By similar reasoning it will be seen that the moment of the couple due to the earth is $m \times$ H $\times$ N D. Now, if the needle has assumed a state of rest, showing that the moments of these two couples are equal, it follows, as a matter of course, that

$$m \times f \times \mathrm{DS} = m \times \mathrm{H} \times \mathrm{ND},$$

and (by cancelling and dividing)

$$f = \mathrm{H}\,\frac{\mathrm{N\,D}}{\mathrm{D\,S}}.$$

The ratio $\frac{\mathrm{N\,D}}{\mathrm{D\,S}}$ is called the tangent of the angle N S D, and this angle is equal to the angle of deflection $a°$ because A B is parallel to L D; consequently

$$f = \mathrm{H} \tan a°.$$

This strength of field, f, is proportional to the current producing it; therefore the current, c_1, is likewise proportional to H tan $a°$.

And this will be true of all currents and all deflections, so that if we let a second current, c_2, cause the needle to be deflected through the angle $b°$, then c_2 must be proportional to H tan $b°$.

Consequently $\quad c_1 : c_2 :: \mathrm{H} \tan a° : \mathrm{H} \tan b°,$
that is, $\quad c_1 : c_2 :: \tan a° : \tan b°,$

or the two currents are directly proportional to the tangents of the angles through which they deflect the needle. By referring to a table such as is here given we can find the numerical value of the

tangents of these or other angles, and so can easily compare the strength of the currents.

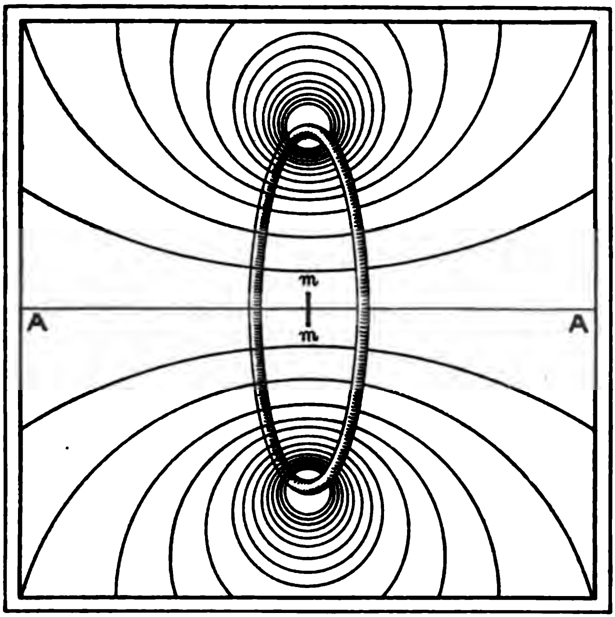
TABLE OF NATURAL SINES AND TANGENTS

Deg.	Sine	Tangent	Deg.	Sine	Tangent	Deg.	Sine	Tangent
1	·017	·017	31	·515	·601	61	·874	1·80
2	·035	·035	32	·530	·625	62	·883	1·88
3	·052	·052	33	·544	·649	63	·891	1·96
4	·070	·070	34	·559	·674	64	·899	2·05
5	·087	·087	35	·573	·700	65	·906	2·14
6	·104	·105	36	·588	·726	66	·913	2·24
7	·122	·123	37	·602	·753	67	·920	2·35
8	·139	·140	38	·615	·781	68	·927	2·47
9	·156	·158	39	·629	·810	69	·933	2·60
10	·173	·176	40	·643	·839	70	·939	2·75
11	·191	·194	41	·656	·869	71	·945	2·90
12	·208	·212	42	·669	·900	72	·951	3·08
13	·225	·231	43	·682	·932	73	·956	3·27
14	·242	249	44	·694	·965	74	·961	3·49
15	·259	·268	45	·707	1·00	75	·966	3·73
16	·275	·287	46	·719	1·03	76	·970	4·01
17	·292	·306	47	·731	1·07	77	·974	4·33
18	·309	·325	48	·743	1·11	78	·978	4·70
19	·325	·344	49	·755	1·15	79	·981	5·14
20	·342	·364	50	·766	1·19	80	·985	5·67
21	·358	·384	51	·777	1·23	81	·987	6·31
22	·374	·404	52	·788	1·28	82	·990	7·11
23	·391	·424	53	·798	1·33	83	·992	8·14
24	·407	·445	54	·809	1·37	84	·994	9·51
25	·422	·466	55	·819	1·43	85	·996	11·43
26	·438	·488	56	·829	1·48	86	·997	14·30
27	·454	·509	57	·838	1·54	87	·998	19·08
28	·469	·532	58	·848	1·60	88	·999	28·63
29	·485	·554	59	·857	1·66	89	·999	57·29
30	·500	·577	60	·866	1·73	90	1·000	Infinite

An instrument which will enable us to make these comparisons is called a tangent galvanometer ; but in order to obtain accurate results one important point must be carefully attended to in designing the instrument, for the foregoing proof only holds good when the two forces forming a pair act parallel to each other in any and every position of the needle. This means, in short, that the field due to the earth and that due to the current must be respectively uniform throughout the entire space in which the needle can be moved. Fortunately we can, by using a very short needle, make this space proportionally small, and thereby render the problem easier. The earth's field, as has been already stated, is sufficiently

uniform, but that due to a current is far from uniform, more particularly in the immediate vicinity of the wire, consequent on the very decided curvature of the lines of force. However, as we get farther away from the wire these lines approximate more and more to straight lines when we consider a certain length of them, say one inch, and if, instead of using a straight wire to carry the current, we bend it into a ring of large diameter, we shall find

FIG. 60



a small space at its centre where the lines of force are, to all intents and purposes, straight and parallel. In fig. 60 is shown a perspective view of the ring and a horizontal view of the distribution of the lines of force in the field. The ellipse, representing the ring itself, has A A for its axis. The magnetic needle is indicated by *mm*. If we suspend the small needle here, the necessary conditions for a tangent galvanometer are satisfied, the needle being

too short to permit of its poles being moved into an irregular or variable part of the field.

With a ring 6 inches in diameter we can, in fact, use a needle three-quarters of an inch in length without the risk of introducing any appreciable error.

Such a ring of wire, then, with a needle suspended at its centre, will serve to compare and measure current strength according to the law which we have just stated—i.e. every current will be proportional to the tangent of the angle through which it can deflect the needle. When made in a practical form, the tangent galvanometer is one of the most accurate and therefore usefuf pieces of apparatus at our command for testing purposes.

It is important to notice here that a variation in the strength of the magnetic needle will introduce no error in the readings; for if, for instance, a needle partly loses its magnetisation or becomes weak, it is acted upon more feebly by both the earth and the current, and in the same proportion, so that the weakened effect of the earth's field is balanced by the equally weakened effect of the current's field. If the student turns again to the equation on p. 103, he will notice that m appears on both sides of the equation, and that it therefore cancels out. It follows that the sensitiveness of a tangent galvanometer is independent of the strength of its magnetic needle. If, therefore, two readings were taken with different needles, but with the same current and with other conditions undisturbed, the deflection would be the same in both cases.

Returning to a further consideration of the laws governing the construction of the instrument, it is essential to remember that the force with which a current deflects the needle is proportional to the length of the wire contained in the coil, and inversely proportional to the square of its distance from the needle. If we increase the size of the coil, we not only increase the distance from the wire to the needle, but we also increase the length of the wire in exact proportion to the increase of the radius. Now the former reduces and the latter increases the effect; and the result may be expressed by saying that the force f, due to the current's field at the centre of the coil whose radius is r, is proportional to

$$\frac{2\pi r}{r^2} = \frac{2\pi}{r}.$$

The quantity 2π is a constant or invariable quantity; whence it follows that the net result of varying the radius of the coil is that the force with which the needle is deflected varies for the same current inversely as the radius of the coil.

It should also be clear that if we use one coil of 3 inches radius, and another of 6 inches radius, the deflection will be the same when the strength of the current in the larger coil is double the strength of the current in the smaller.

With, however, a single turn of wire 6 inches in diameter only comparatively strong currents can affect the needle, and, as we have seen, it is not permissible to reduce this diameter for the purpose of obtaining an appreciable deflection with comparatively weak currents. But the difficulty can be easily overcome, for we can increase the length of the wire, without increasing the distance from the needle, by the simple device of coiling it round the needle a number of times. Since the effect on the needle varies directly as the length of the wire, and the length of wire in two turns is double that in one turn, the effect on the needle is doubled also; in other words, the effect on the needle varies directly as the number of turns of wire in the coil. It follows that, with equal currents, a 6-inch coil of one turn will give the same deflection as a 12-inch coil of two turns.

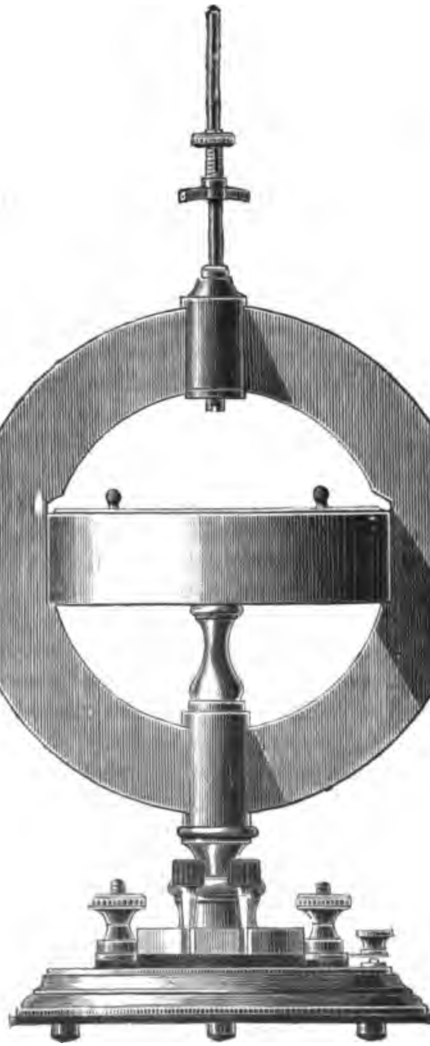
It must be remembered, however, that if the number of convolutions is increased to any great extent the resistance becomes considerable, and the very act of inserting the galvanometer in a circuit may then appreciably decrease the current we desire to measure.

Bearing all these points in mind, we will now consider a practical instrument for the measurement of current strength, selecting for description one form, of which a general view is shown in fig. 61.

The casing is of brass. The mean diameter of the coil is $6\frac{1}{2}$ inches; the width of the channel in the brass ring which contains the wire is $\frac{5}{16}$ inch, and its depth $\frac{7}{8}$ inch. The length of the needle—which is carefully pivoted with agate on an iridium point—is $\frac{3}{4}$ inch.

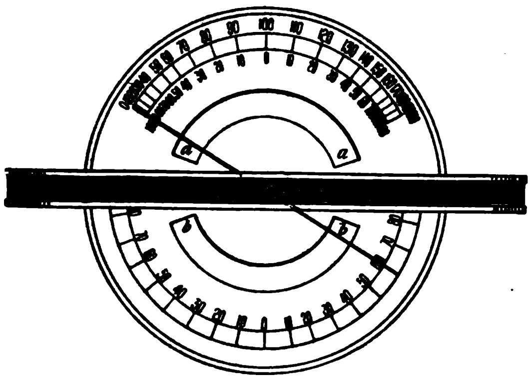
As this needle is too short to indicate its own deflections, it carries a light pointer of gilt copper wire, about 5 inches in length,

FIG. 61



fastened to it at right angles. This pointer moves over an engraved circular scale-plate, one half of which is divided into degrees, the other half into divisions corresponding to the tangents of those degrees, as shown in fig. 62.

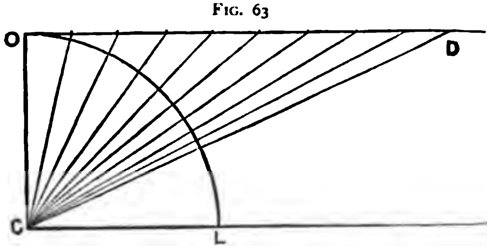
FIG. 62



It may be of service if we refer here to the manner in which this tangent scale is constructed.

Let the quadrant O L (fig. 63) represent a portion of the circle along which the scale is to be marked, and let C O be the radius

FIG. 63



along which the index needle is to point when at rest under the influence of the earth's magnetic field, and when therefore no current is circulating through the coil of the instrument. Then draw the tangent line, O D—that is to say, a line at right angles to O C, meeting it in O. Then mark off along O D any number of

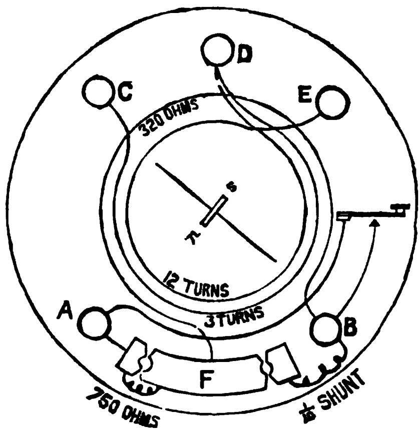
equal divisions, and project lines from these points or divisions to C, the centre of the circle, intersecting the circumference at various places. These points of intersection will then correspond to the equal divisions along O D, and will be proportional to the tangents of the various angles which would be measured at those intersections. This device saves the operator the trouble of ascertaining from a table the tangent equivalents to the various deflections and then calculating their relative values, as would be necessary were the scale divided into degrees in the usual manner.

A piece of looking-glass is placed under the scale-plate and is exposed at two curved slots in the plate (*a a* and *b b*, fig. 62), so that in taking a reading the observer may let the pointer cover its own reflection, when he will be assured that he is looking vertically down upon it, avoiding thereby any error due to parallax—that is to say, any inaccuracy in reading caused by looking at the pointer sideways. A lever, operated by a small switch extending through the box which carries the needle and scales, is provided for lifting the needle off its pivot when not in use. There is also (see fig. 61) a small adjustable magnet which slides on a vertical brass rod over the needle, and is used for varying the sensitiveness of the instrument. By this means it is possible to make such an adjustment that a given deflection—say twenty-five divisions—is produced by a current of one milliampere, and it is frequently very convenient to so adjust the instrument when using it for some classes of work. The controlling magnet, when placed with its S. pole over the N. pole of the needle, assists the directive force of the earth's magnetism, or helps to keep the needle in the meridian with its north-seeking pole pointing to the north. The effect is the same as would be the case were the strength of the earth's field increased, and a stronger current is then required to produce any given deflection. Hence the sensitiveness of the instrument is reduced. On the other hand, if the controlling magnet is placed with its north-seeking pole pointing northwards, it tends to turn the needle round from the zero position; and therefore its effect is the same as would result from a reduction in the strength of the earth's field, whence the sensitiveness of the instrument is increased. Either effect may be varied in magnitude by sliding the magnet up or down the rod, and thus varying its

distance from the needle. For instance, the needle will give the least deflection with a given current when the magnet is placed at the bottom of the rod with its poles assisting the earth's magnetism.

A reference to fig. 64 will make the conception of the electrical portion of the instrument easier. There are three separate coils of wire in the brass ring, or bobbin, the ends of each being brought down through the hollow pillar and connected under the base of the instrument to their respective terminal screws, as shown in plan on the figure. Between the terminals C

FIG. 64



and D is a coil consisting of three turns of thick wire ; between D and E are twelve turns of similar wire, but wound in the opposite direction. If the current be sent from C to E, we get nine turns acting on the needle, for three of the twelve turns are neutralised by the three in the opposite direction between C and D. The resistance of these coils is negligibly low, so that we are able to get the effect from three, nine, or twelve turns without varying appreciably the strength of the current. The other coil consists of a great many turns of fine silk-covered wire. Its resistance is exactly 320 ohms. One end of it is joined to terminal B, and the other end to the middle brass block F. By inserting a brass plug

in the left-hand hole, the end of the coil attached to the middle block is connected to terminal A direct. If, however, this plug is removed, the current in travelling, say, from B has to pass through an additional resistance coil of 750 ohms (which is fixed under the base of the instrument) before it reaches terminal A. Under these circumstances the total resistance between A and B is 1,070 ohms. Suppose now a single Daniell cell, whose resistance is comparatively low and whose E.M.F. is 1·07 volt, to be joined to terminals A and B. By Ohm's law the current is equal to $\frac{1{\cdot}07 \text{ volt}}{1070 \text{ ohms}}$, or ·001 ampere—that is, 1 milliampere.

These resistances are, in fact, calculated for use with a single Daniell cell as a standard. We can therefore always immediately produce a deflection which we know to be that due to 1 milliampere of current, and find the value of any other current by observing its deflection under similar conditions. A small key is fixed on the base of the instrument; when depressed it connects A direct to B, as will be seen by fig. 64, or, in the usual language, it short-circuits the coils. It is used for checking the oscillations of the needle and bringing it quickly to rest. The 750-ohm coil should always be cut out of circuit except while the instrument is being 'standardised,' as explained above.

It is sometimes required to measure a current so strong that the deflection is inconveniently high. In this case a part of the current may be 'shunted,' or provided with a by-path, so that only a portion of the current shall go through the galvanometer, the rest going through the shunt. It is necessary, however, to know exactly what fraction of the total current is passing through the instrument and what through the shunt. If we join the ends of the coil by a shunt equal to it in resistance, then the current will divide equally between the two paths, and only half of the total current will be measured. If the resistance of the shunt be $\frac{1}{9}$ that of the galvanometer, then $\frac{9}{10}$ of the current will pass through the shunt and the remaining tenth through the galvanometer. In this case, therefore, the total current will be ten times that measured by the deflection of the needle.

The instrument we are now describing is provided with such a shunt; its resistance is $\frac{320}{9}$ ohms, and fig. 64 clearly shows how it

may be brought into use by inserting a plug in the right-hand hole, thus connecting together the middle and right-hand blocks. Suppose, when the adjustment is such that 1 milliampere gives twenty-seven tangent divisions, that we insert this one-tenth shunt, and then with a current of unknown strength obtain eighty-one divisions. The current flowing round the galvanometer is manifestly 3 milliamperes; but this is only $\frac{1}{10}$ of the whole, consequently the total current is 30 milliamperes.

In order to reduce the current flowing through a galvanometer to any fraction of its full value, say to $\frac{1}{n}$, the resistance of the shunt necessary to produce that result must be $\frac{1}{n-1}$ of that of the galvanometer. A moment's reflection, however, will make it evident that the introduction of a shunt reduces the resistance of the circuit, and may, therefore, cause a considerable and material increase in the current strength. Where this increase of strength is appreciable, the introduction of extra resistance sufficient to compensate for the fall caused by the shunting becomes necessary, the problem being to ascertain exactly how much compensating resistance is required. By the laws of the joint resistance of two parallel wires explained in Chapter II., the joint resistance of the galvanometer G and the shunt S will be equal to $\frac{\text{G S}}{\text{G} + \text{S}}$. Now the resistance of S has just been shown to be $\frac{1}{n-1}$ part of G, or $\frac{\text{G}}{n-1}$: that is, if only a tenth of the current is to pass through the galvanometer, the shunt resistance should be $\frac{1}{10-1}$, or $\frac{1}{9}$ part of the galvanometer resistance G. That is to say, $\text{S} = \frac{\text{G}}{n-1}$, and inserting this value we get as the joint resistance—

$$\frac{\text{G S}}{\text{G} + \text{S}} = \frac{\text{G}\,\frac{\text{G}}{n-1}}{\text{G} + \frac{\text{G}}{n-1}},$$

which is equal to $\frac{\text{G}}{n}$.

So that the joint resistance of a galvanometer of 320 ohms and its one-tenth shunt will be $\frac{G}{n} = \frac{320}{10} = 32$, whence it follows that the reduction in resistance due to the use of the shunt amounts to $G - \frac{G}{n}$, or $320 - 32 = 288$. 288 ohms is, therefore, in this case the resistance that it would become necessary to introduce in order to restore the resistance of the circuit to the same value that it had prior to the introduction of the shunt. And, generally, it may be said that the introduction of a shunt reduces the resistance of the circuit to the extent of $\frac{n-1}{n}G$, and that amount of resistance will need to be inserted in order to re-establish the conditions of the circuit. In short, this compensating resistance is equal to the difference between the resistance of the galvanometer alone and that of the galvanometer shunted.

When great accuracy is desired, all the readings on the tangent galvanometer should be taken with the needle deflected as nearly as convenient through an angle of 45°. The reason for this is, that any given proportional increase or decrease in the strength of the current will produce a greater effect on the needle when it is in that position than when in any other, or, in other words, the sensitiveness of the instrument is then at its maximum. For instance, if, when the needle is deflected through 45°, an increase of the current by one-fortieth gives an increase of one division in the deflection, a similar increase in the current when the needle stood at 10° or 80° would not be perceptible. When the deflection is small, the current is so low that a small given fraction thereof is insufficient to appreciably increase the deflection; while when the deflection is very high, the opposing moment due to the earth's magnetic field is comparatively great, and further, the divisions on the scale are too crowded to enable a very accurate reading to be taken.

Every galvanometer has a definite *angle of maximum sensitiveness*, or such an angle of deflection that with a given proportional increase in the strength of the current there will be a larger divergence than when the needle is at any other point on the scale, and for every tangent galvanometer the angle of maxi-

mum sensitiveness is 45°. We should always endeavour, therefore, when using this instrument, to get the deflection as near 45° as possible, or when comparing two currents get the deflections at equal distances on either side of this point.

It has already been pointed out that it is very convenient in practice to be able to determine immediately the value in amperes or milliamperes to which some particular deflection of the needle corresponds, and it will be remembered that with a Daniell cell as a standard a current of 1 milliampere may be immediately produced; but it must not be forgotten that, owing to the alteration in the directive force consequent upon moving the instrument, or moving pieces of iron in its vicinity, it is essential that a standard reading should be taken prior to each test or series of tests. The experimenter should also guard against any such prejudical effect as would result from a bunch of keys or a knife carried in the pocket, or the wearing of steel-rimmed spectacles during a test.

The foregoing applies to a galvanometer with a tangent scale constructed so that its zero point is in the centre, as is the case with the *inner* scale on the tangent divisions side in fig. 62. But it will be seen that in this figure there is an outer scale, also of tangent divisions, with the zero point at the extreme left hand, where the pointer is shown resting. This outer scale is known as the 'skew scale,' a term derived from the position of the needle when at this zero, and its great advantage lies in the fact that its range of measurement is double that of the ordinary scale. For a comparatively high reading, also, the deflection can be read with greater ease, as the pointer is not in the part of the scale where the divisions are close together. It is true that a small deflection from this zero cannot easily be read, on account of the closeness of the division marks, but the ordinary scale can be employed for such currents.

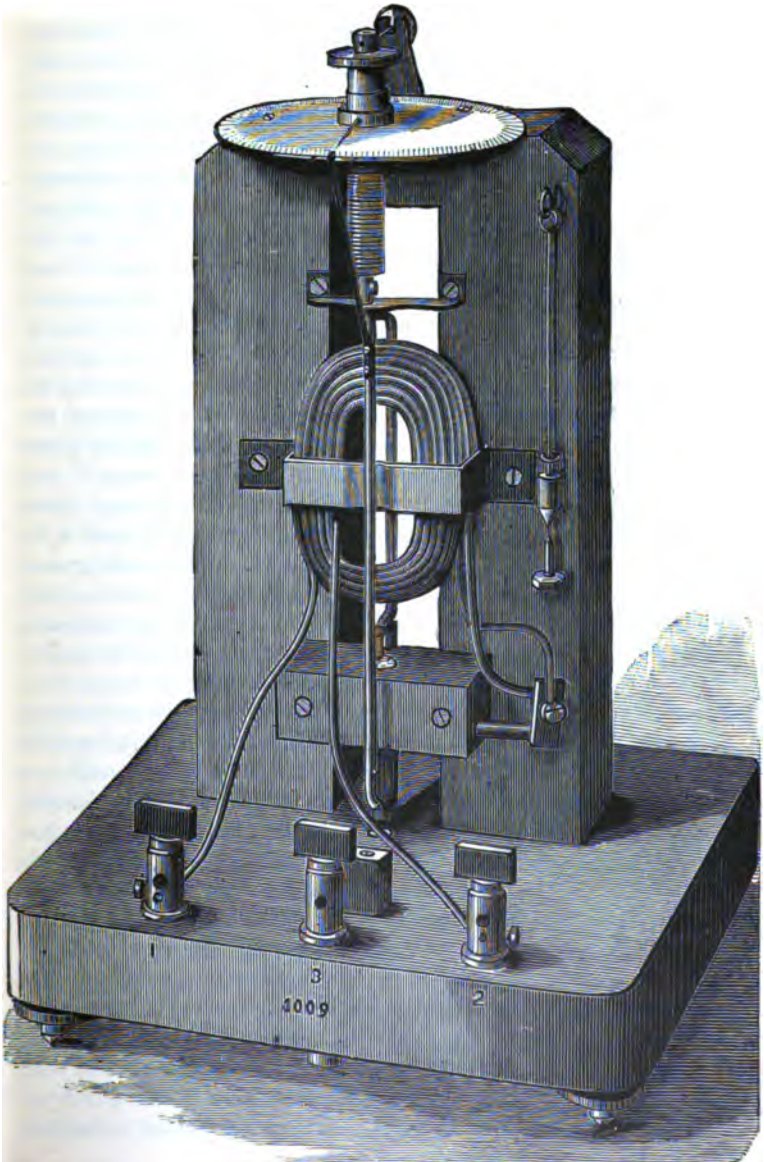
Unfortunately, the tangent galvanometer is but little suited for the measurement of powerful currents such as those generally employed in electric lighting and many other branches of electrical engineering. We must, therefore, now direct attention to an instrument which will to a considerable extent answer this purpose, and one which, when skilfully used, is remarkably accurate. It is based upon the simple experiment mentioned at the commence-

ment of this chapter—viz. the attraction or repulsion which takes place between two wires carrying currents. It may now be stated that the force of this attraction or repulsion is readily measureable, being, in fact, proportional to the strength of one current multiplied by the strength of the other, provided that the distance between the two wires remains constant. If we suppose the currents in each of the wires to be exactly equal, say 2 amperes, then the force may be represented by the number $2 \times 2 = 4$. Now if we double the current strength in each wire, the force of attraction or repulsion will be $4 \times 4 = 16$; so that, when the current strength in each is doubled, the force between them is quadrupled. Similarly, if we treble the current in each wire, or make it 6 amperes, then the mutual force will be $6 \times 6 = 36$, or nine times as great as when the current was 2 amperes. We therefore see that the force of attraction or repulsion between two wires carrying equal currents varies as the square of the current strength. It will be apparent that the simplest method of obtaining equal currents in each wire is to join them in series, and allow the same current to flow through both. Then, if any number of currents be successively sent through them, the force of the action between the wires will be proportional to the square of the strength of the current in every case; whence it may be reasoned that if these forces can be measured or compared, the currents producing them can also be estimated, for, since the force varies as the square of the current, the current will vary as the square root of the force exerted by it.

In constructing an instrument on this principle, it is necessary, therefore, to have some means of accurately indicating the force exerted, and also to ensure that the distance between the wires remains exactly the same during all the comparisons.

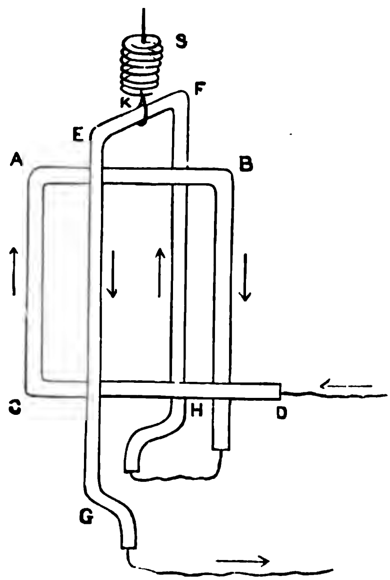
The Siemens dynamometer fulfils all these conditions to the letter. A general view of this instrument is given in fig. 65, fig. 66 showing the manner in which the principle is applied. The two wires (or coils) are rectangular in shape. One of them, A B C D (fig. 66), is rigidly fixed to a vertical support, while the other, E F G H, which is sufficiently large to embrace the fixed coil when the plane of the one is at right angles to that of the other, is suspended by a stout silk thread. In order that the current

Fig. 63



may be passed through the movable coil, without in any way impeding or interfering with its freedom of motion, its two ends, G and H, are brought round and bent down into mercury cups placed vertically one over the other, so that the two ends and the point of suspension, K, are in the same vertical line. Connection with the mercury is made by a wire passing in at the bottom of the cup. The arrows in fig. 66 show the direction of the current in the various parts of the circuit, when a current is sent through both coils in series, and it is easy to see that each vertical limb of the movable coil will be urged, by repulsion on one side and attraction on the other, to set itself in the same plane as the fixed coil. But it has already been said that it is essential that the coils should remain or be brought back into the same relative positions when the force between them is measured. In the Siemens dynamometer the position selected is with the planes of the two coils at right angles; and the force measured is that force which is necessary to keep the movable coil in this position against the turning effort due to the current.

FIG. 66



This antagonistic force is applied by means of a spiral spring, S, the lower end of which is rigidly fixed to the rectangle E F G H, while its upper end is fixed to a mill-headed screw, which can be turned round, torsion being thereby applied to the spiral spring. A pointer is attached to the screw-head and moves with it, and, travelling over a graduated scale, divided usually into 400 equal divisions instead of 360 degrees, indicates the amount of torsion

applied to the spiral spring in bringing the coil s s s s back to the zero position against the opposing force due to the current circulating in the coils. It is a simple and well known law that the force of torsion is proportional to the angle of torsion, and as the angle through which the screw is turned in order to keep the movable rectangle at zero is an exact measure of the torsion applied, the force necessary to the production of that angle must be proportional to the force acting between the two coils and due to the current circulating in them. This latter force varies as we have seen, as the square of the current strength, so that, therefore, the current is proportional to the square root of the angle of torsion. The movable coil also carries a pointer, the end of which just overlaps the scale-card and plays between two pins about half an inch apart. When it points to zero, the two coils are accurately at right angles one with the other.

The instrument has usually two separate and distinct fixed coils, one consisting of a few turns of thick wire, and the other of a larger number of turns of a thinner wire. The object of this arrangement is to facilitate the measuring of currents differing very considerably in strength, and so to increase the available range of the instrument. One end of the thin wire coil is joined to the left-hand terminal screw (fig. 65), and one end of the thick wire coil to the right-hand screw. The other two ends are connected to the upper mercury cup, while the lower cup is joined to the middle terminal screw.

For a strong current, then, the centre and right-hand terminals, giving the thick wire and movable coils, should be used; while for a weaker one the centre and left-hand terminals, between which are the thin-wire and movable coils, should be employed.

On account of the operation of the law of the square, a more accurate reading can be obtained in the higher part of the scale than in the lower, and it is therefore, where possible, more advantageous to use the thin-wire coil for such currents as would give only a low reading with the thick-wire coil.

Three levelling screws are provided, it being absolutely essential that the coils should be exactly perpendicular. The movable rectangle can be raised or lowered by means of the

thread which is attached to a horizontal screw at the top of the instrument, until it moves quite freely and makes good contact with the mercury. It is difficult to replace this silk thread quickly, and this constitutes a weak point in the instrument, for an inexperienced operator frequently commences his experiment by breaking it.

The instrument requires calibration—that is to say, it is necessary to find out to what current strength a certain amount of torsion is equivalent—before any unknown current can be measured in amperes. This calibration may be effected by deflecting the rectangle by a current of known strength, and then by turning the milled head attached to the upper end of the spiral spring, applying just sufficient torsion to restore the pointer attached to the rectangle to the zero position. Suppose the current to be 1 ampere and the torsion applied 16 divisions. Then if a current of unknown strength be sent through the same coil, and it is necessary to apply 64 divisions of torsion to bring the rectangle back to zero, the latter current will be 2 amperes in strength; for

$$C_1 : C_2 :: \sqrt{16} : \sqrt{64},$$

that is, as 4 is to 8 or as 1 is to 2.

In practice such calculations would be exceedingly inconvenient; the makers therefore calibrate the instrument, or determine what strength of current corresponds with the various angles of torsion, both for the thin- and thick-wire coils. These results are tabulated in a convenient form and supplied with the instrument.

On referring to fig. 66 it will be observed that, if the current is reversed, the rectangle will still be deflected in the same direction, because, the direction of the current in *all* the limbs being altered, attraction or repulsion will take place between the same limbs as before. The instrument can therefore be used to compare either positive or negative direct currents, or even alternating currents—i.e. those whose direction is rapidly reversed.

The pointer attached to the screw-head should always stand at zero when the instrument is not in use, otherwise the spiral spring will take up a *set* and will not bring the rectangle to zero

when the pointer is brought there. The spring will, however, gradually recover from any such set if it be not excessive.

The Siemens dynamometer is a very accurate instrument when used with ordinary care, but every measurement occupies an appreciable amount of time, for in every case the rectangle has to be brought back exactly to zero, the amount of torsion noted, and then the table referred to, to ascertain the current strength to which this torsion corresponds. The currents which can be measured by the dynamometer, although much above the range of the tangent galvanometer, are too small for present-day practice, and although a large number is still in use, other instruments are gradually supplanting it.

It should also be evident that an instrument which immediately indicates in amperes the strength of the current flowing is far more convenient to use, although even now there are not many *direct reading* instruments which can be relied upon to remain accurate for so great a length of time as the Siemens dynamometer.

Instruments which directly indicate the current strength in amperes are called ammeters, and such instruments usually require to be calibrated by comparison with a standard instrument. Perhaps the most important series of standard measuring instruments which have yet been designed are those due to the inventive genius of Lord Kelvin. They are based upon the same laws as the Siemens dynamometer, viz. that repulsion or attraction takes place between two adjacent conductors carrying currents, according to the direction in which the currents respectively flow.

In fig. 67 is illustrated one of these instruments, which are known as Ampere Balances, and are made in a series of ranges. The particular instrument illustrated is the Deci-ampere balance, which is designed for a range of 0 to 10 amperes, but this instrument corresponds in all essential details with the other balances ranging in measuring capacity up to 600 amperes. The movable conductor consists of two flat circular coils, which are fixed in a horizontal plane at the ends of a horizontal beam whic is capable of rocking through a very small arc. The fixed conductor consists of four flat circular coils, one placed above, and one below, each of the movable or rocking coils. The

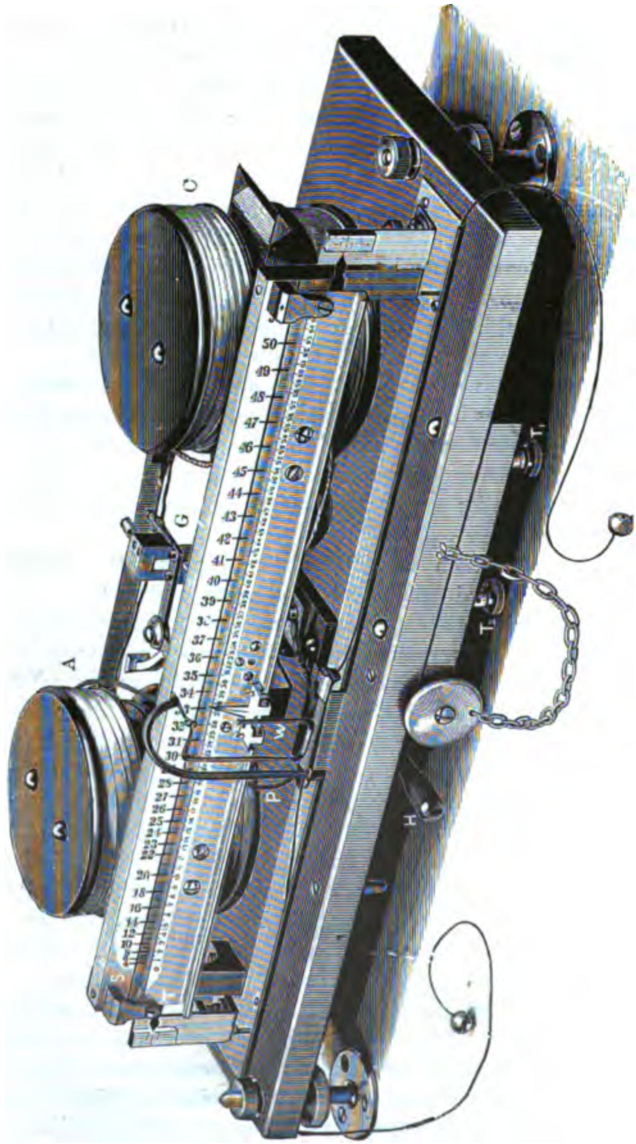
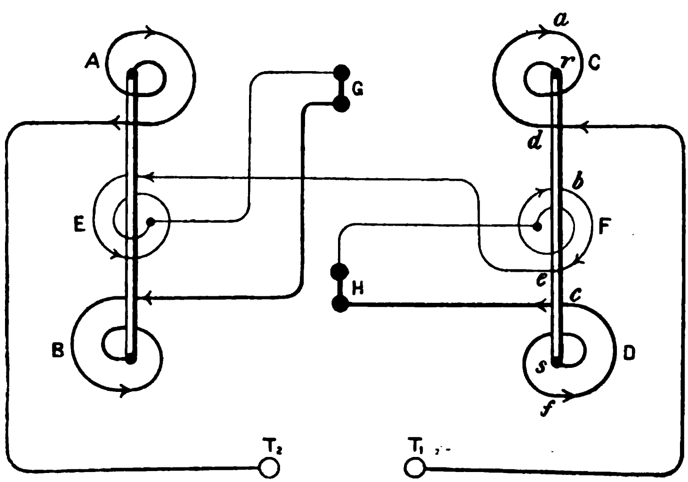


Fig. 67

position of the movable coils is approximately midway between the fixed coils. All six coils are joined in series, and the connections, together with the underlying principle of the instrument, may be gathered from the diagram fig. 68. Where the arrows indicate the direction in which the current flows in the various parts of the instrument, A B C D represent the fixed coils, E F the movable coils, and G H the suspension ligaments, to which a further reference will be made later. These six coils are at the back of the instrument, as shown in fig. 67, but A and C,

FIG. 68



which are the upper fixed coils, can be easily seen. T_1 and T_2 represent the terminals in both figures. Assuming the current which is to be measured to enter by terminal T_1, it will pass (fig. 68) to the upper fixed coil C, and traversing that coil will then pass in the reverse direction through the lower fixed coil D. On leaving that coil, it will pass through the suspension H to the movable coil F, the direction of the current round the coil being clearly shown by the arrows. In order to avoid any misapprehension as to direction of the current in the various parts of the coils, the connection between the centres *r* and *s* has been shown

as a solid rod, although, of course, such a device is not necessary, nor is it resorted to in practice. It will, however, be evident that *a* *b* and *c* represent the back portions of the convolutions, while *d* *e* and *f* represent the front portions. Now the currents in *a* and *b* are in the same direction, and are therefore mutually attractive, (see fig. 35). Similarly the currents in *d* and *e* are uni-directional, and are also mutually attractive, so that there is attraction between the coils C and F. Conversely the currents in *b* and *c* and in *e* and *f* are opposite in direction, whence the coils F and D are mutually repellent. In other words the passage of the current in C tends to *draw* F up, and in D to *drive* it up. If the coils A E B on the left side be similarly studied, it will be seen that when the current is such as to cause the coil F to rise, it will at the same time strive to depress the coil E.

If the direction of the current through the instrument were reversed, the whole of the arrows would also be reversed, so that in either case the effect would be a tendency to tilt the pair of movable coils in the same direction, depressing the left hand and raising the right hand side. Of course the direction of the current in the coils A E B could be reversed, so as to make the direction in E and F the same, and still to retain the rocking tendency, but by making the currents traverse the movable coils in opposite directions possible disturbances which might arise from local magnetic forces are annulled. In the large-sized ampere balance known as the special Kilo-ampere balance, and measuring up to 2,500 amperes, the whole current passes through a single fixed coil or ring, and divides through two halves of a movable ring which are urged, one up and the other down, by the resulting force.

In every instrument of this class the movable coils are, however, kept in or restored to a horizontal position by means of a weight (W, fig. 67), and the current strength tending to deflect the pair of movable coils is deduced from the value of the weight and its position on the scale when the balance is restored. One of the features of the instrument is the arrangement for conducting the heavy current to and from the movable coils without risk of impeding their movements or heating the supports. This is effected by supporting the balance arm, or the beam carrying the

movable coils, by two trunnions each hung by an elastic suspension ligament consisting of a bundle of very many fine copper wires (G, fig. 57, and G H, fig. 58) through which the current passes. The readings being taken when the movable coils are in the zero position, it is only necessary to ensure perfect freedom of motion through a small distance on either side of zero, and this condition is perfectly satisfied by the suspension arrangement adopted.

In balances constructed for measuring currents up to 1,000 or more amperes, the main current through each ring is carried by a wire rope, each component wire being insulated from its neighbour in order to prevent the inductive action from altering the distribution of the current across the transverse section of the conductor; for were the conductor solid there would be the risk that the current would be largely confined to the outer portions of the wire or rod, only a comparatively small portion of it passing through the central portion of the conductor. This phenomenon will be more fully referred to in the chapters dealing with dynamo construction; but it may here be observed that this phenomenon arises from the fact that the attraction or repulsion, as the case may be, is between the currents rather than between the conductors conveying them, or, in other words, the conductors are moved because they are the media through which the currents pass.

The cross section of the conductor used for winding the coils in the various sizes of the instrument is proportioned to the maximum current which the particular instrument is designed to measure, and the design is such that any instrument can transmit or carry 75 per cent. of its maximum load continuously, and can also carry the full load long enough for standardising purposes.

Reverting to fig. 67, the forces exerted by the attraction and repulsion upon the movable coils is balanced by the sliding steel yard weight W previously referred to. This weight slides on an equally divisioned fine scale R, graduated directly on the beam attached to the balance. In order to give a long range to each instrument four weights in all are supplied, the carriage alone constituting the first weight.

For the fine adjustment of the zero a small metal 'flag' is provided, as in the ordinary chemical balance. This flag is actuated by a fork, having a handle, H, outside the case, as shown in the figure. In order to set the zero, the sliding weight is placed with its pointer at the zero of the scale, and the flag is turned to the one side or the other until it is found that with no current passing through the coils the balance rests in its righted position. A fixed inspectional scale, S, graduated with bolder numbers and divisions, is arranged immediately behind the fine scale R, notches being provided along the top edge of the fine scale to correspond with each of the principal divisions of the inspection scale S. A certificate is supplied with every instrument, and constants are provided for each weight which apply to the values on the inspectional scale. It is necessary in the course of measuring a current to slip the weight along the scale until the balance again rests in its sighted position. The strength of the current can then be read off directly from the fixed or inspectional scale S. Each number on that scale is a figure which is twice the square root of the corresponding number on the fine scale of equal divisions. This scale shows approximately the current strength: that is to say, within a small fraction of the exact value, but when extreme accuracy is required, the reading on the fine divided scale R must be taken and the exact value of such reading found by reference to the table of 'double square roots' supplied with the instrument.

The slipping of the weight into its proper position is performed by means of a self-releasing pendant P, hanging from a hook carried by a sliding platform, which is pulled in the one or other of the two directions by means of two silk threads which pass through holes to the outside of the glass case.

As we have already said, four pairs of weights are supplied with each instrument. These weights are adjusted in the ratios of 1, 4, 16, and 64, so that each pair gives a round number of amperes, or half-amperes, or quarter-amperes, or of decimal subdivisions of these magnitudes of current on the inspectional scale S.

The balance, as it contains no iron, is suited for the measurement of either direct or alternating currents.

The instruments for measuring the smaller currents have of necessity considerable resistance, and for that reason, if for no other, they are unsuitable for use as ordinary ammeters. But as they are usually employed in series with an ammeter for the purpose of calibration, this high resistance is a matter of little moment.

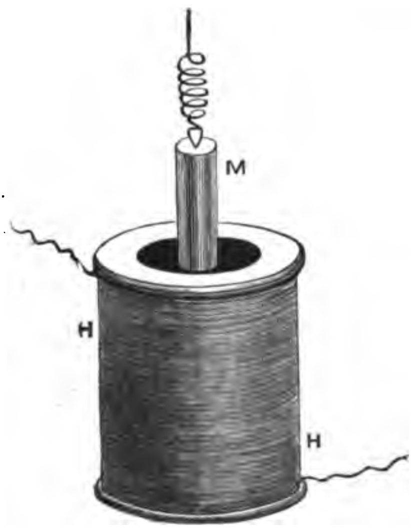
Some skill is required to use these balances effectively, but a good method of quickly calibrating an ammeter is to first set the balance weight in a position corresponding to a definite current, and then adjust the resistance in circuit until the balance indicates that that exact current strength has been obtained. The position of the ammeter needle for this current can then be noted and other readings can be obtained in a similar manner.

Coming now to the question of direct reading ammeters, they may generally be divided into two classes, (*a*) those in which a piece of soft iron is so supported in a coil of wire that in the passage of a current through the coil the iron will be attracted into a more powerful part of the field, and (*b*) those in which a coil of wire is so placed in a powerful field that when a current passes through the coil it will be deflected or rotated, so that the field set up by the coil shall be able to coincide more or less closely with the permanent field. The former class is known as moving iron instruments, and the latter as moving coil instruments.

Dealing first with the principle involved in the construction of the moving iron ammeter, it is important to observe that if a magnetic field is not uniform, a piece of soft iron, if placed in a comparatively weak part of the field, will be urged toward the strongest part, and the extent of the movement will depend upon (*a*) the strength of the field; (*b*) the mass, shape, and position of the iron; and (*c*) the friction or other restraining means provided to resist the effort of the field, and to restore the iron to its original position on the cessation of the current. One such arrangement is illustrated in fig. 69, which consists of an iron rod, M, supported by a spring placed with its lower end just inside the helix of wire H H. If a current be circulated in the helix a magnetic field will be set up which will extend sufficiently beyond the end of the helix to partially magnetise the iron rod and convert it into a temporary magnet, and as a consequence it will be sucked down into the

helix, and if the magnetic field be sufficiently strong the action will result in the spring being extended sufficiently to allow the iron to be sucked down until the middle of the iron reaches the middle of the helix, in which position it will be in the strongest part of the field. The extent of the sucking down will, with any given piece of apparatus, be proportional to the product of the strength of the field and the strength of the temporary magnetisation set up in the iron by that field. The strength of the magnetic field is proportional to the strength of the current flowing through the helix, and the strength of the temporary magnet varies in any particular position with the strength of the field, but being only a mass of soft iron depending for its magnetisation upon the field set up by the current, the extent of its magnetisation is not definable by a regular law. The readings of the instrument as determined by the extent to which the iron is drawn into the helix will not therefore be proportional to the strength of the current flowing through the helix, unless by some means the strength of the temporary magnet can be kept constant.

FIG. 69



Experiment shows, however, that, although the magnetic lines of force pass readily through a piece of iron when there are very few lines already there, yet, when a great many are present, any further addition to their number becomes extremely difficult. When in this latter condition the iron is said to be 'saturated.' A piece of *very thin* soft iron tubing becomes saturated even in a weak field—that is, in a field traversed by but few lines of force; so that beyond a certain stage, although the strength of the field

may be increased, the number of lines of force passing through the iron tubing—that is, its strength considered as a magnet—remains practically the same. Therefore, if we use a very thin tube of soft iron, the force with which it is sucked into the helix will, for all fields above a certain strength, depend simply upon the strength of the field and will be proportional thereto, and consequently also proportional to the strength of the current producing the field.

Except for weak currents, then, we may estimate the strength of a current by measuring the pull on such a thin tube of iron placed partly inside a helix. It must not, however, be placed exactly in the middle of the length of the coil, as that, being as we have already indicated the strongest part of the field, is the position of rest for the iron.

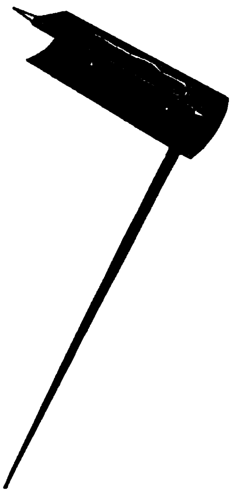
FIG. 70

Many instruments have been designed on this principle, ingenuity being chiefly exercised in the method of measuring the pull or attractive force upon the piece of iron and in the device for restoring the iron and likewise the indicating needle to zero on the cessation of the current. In an instrument devised by Professors Ayrton and Perry, but which has in recent times been superseded, the method was very ingenious. It depended upon a peculiar property possessed by a flat spiral spring shaped like a curled-up shaving, as illustrated in fig. 70. If such a spring be stretched while one end of it is fixed, the other end will rotate, and the angle of rotation will be exactly proportional to the amount of stretching, the angle being considerable even for a small extension of the spring.

A spring of this kind was placed in a thin iron tube and attached to it at the lower end. The upper or free end of the spring was rigidly fixed, so as to be incapable of rotating, while the tube was free to rotate, but was prevented from moving laterally. Therefore, when the tube which extended some distance into the coil was sucked down, the lower end of the spring rotated, carrying with it the tube. The upper end of the tube which projected out of the coil for a short distance carried a pointer which moved over a graduated scale and so indicated the

angle of rotation, the usual horizontal mirror being provided to avoid errors due to parallax. The scale could, of course, be divided, so as to represent amperes or fractions of an ampere, but as iron does not become saturated until the current has attained a certain strength, the first portion of the scale was never used, and was in fact not graduated. It is clear that if the iron tube moved through any considerable distance so as to get into a relatively more powerful part of the field, the readings would not be proportional; but it will be remembered that the peculiarity of the spring is that the angle of rotation is great for a very small elongation: consequently the pointer traversed the whole range without the distance through which the iron moved being sufficient to cause inaccuracy. This was one of the earliest ammeters designed for practical work, but it had among other disadvantages that of having a horizontal scale, so that it had to be fixed on a table or bracket at a convenient height for reading purposes.

FIG. 71



An instrument with a vertical scale is far more convenient, since the movements of the pointer can be seen at a distance. A number of such instruments have from time to time been constructed which depend upon the power of a coil, arranged with its axis in a horizontal direction, to raise a more or less weighty piece of iron against the force of gravity. They all require to be calibrated, but under the circumstances that is not a serious objection, providing that the calibration is correctly performed and that the value of the various readings remains fairly constant for a considerable time.

A view of the moving portion of one of these instruments is given in fig. 71. A light steel arbor or spindle is pivoted so as to lie parallel to, and a little to the left of, the axis of the coil. It has attached to it a thin curved plate of soft iron shaped as shown in the figure. This piece of iron is nearly equal in length

to the arbor, and extends through the length of the solenoid. A light aluminium pointer is also fixed to the arbor at right angles, and the movable parts are so weighted that, in the absence of a current, the pointer is held in the zero position by the force of gravity.

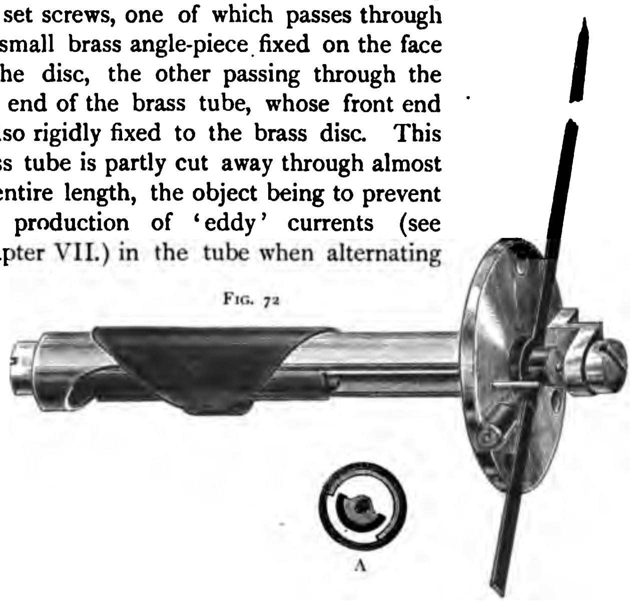
A current passing through the coil in endeavouring to rotate the curved piece into the centre or densest part of the magnetic field raises it against the force of gravity through a distance depending upon the strength of the current. The index or pointer attached to the arbor travels, therefore, over the scale which is placed behind it, and thus indicates the strength of the current passing through the instrument. A small piece of copper wire is attached to the upper side of the arbor, and has to be carefully and skilfully adjusted in order that a uniform scale may be provided. The gross weight of the moving part is but $\frac{1}{30}$ of an ounce; the amount of friction is therefore very slight. The instrument was at one time very popular, but has dropped out of general use, and is only referred to as illustrating the process of development in the construction of measuring instruments.

As an illustration of present day practice we may describe the 'Electric Gauge,' designed by Mr. S. F. Evershed. It is the descendant of the so-called 'Gravity' ammeter, and is an excellent piece of apparatus for ordinary work where extreme accuracy is not required. As there is in this, as in other moving-iron ammeters, no permanent magnet employed, the mains may be joined up indiscriminately: that is to say, the current may travel through the coil in either direction, because the only field set up is the one due to the current, and the iron is only energised by that field. As a consequence the pointer moves in the same direction, for a continuous current in either direction. Of course there would be a risk of error due to the retentivity of the moving iron were it not that it is very thin and very soft, so that its magnetisation can be readily and completely reversed. The instrument can even be adapted for the measurement of alternating currents.

The magnetising coil is placed with its axis horizontally, so that the dial over which the needle or pointer travels is vertical.

That part of the instrument which is placed within the coil is frequently called a 'plug,' and is of exactly the same construction for ammeters and volt-meters of all sizes, whether for alternating or direct currents. Fig. 72 illustrates this important part of these instruments. A horizontal brass spindle is pivoted in the ends of two set screws, one of which passes through the small brass angle-piece fixed on the face of the disc, the other passing through the rear end of the brass tube, whose front end is also rigidly fixed to the brass disc. This brass tube is partly cut away through almost its entire length, the object being to prevent the production of 'eddy' currents (see Chapter VII.) in the tube when alternating currents pass through the coil, and a small curved iron 'needle' which is carried by the spindle can be seen through the opening.

FIG. 72



A peculiarly shaped piece of sheet iron embraces the fixed brass tube, to which it fits, friction-tight; it is cut away, as shown on the side visible in fig. 72, but is continuous on the side which is hidden from view. The top of the pointer moves from left to right over a scale when deflected from zero, and in the position shown in the figure it is deflected through about half its entire range. The action is not difficult to understand: when a current passes through the coil which envelops the plug, a field of force is set up in which the lines are parallel with the plug, and as many of them as possible endeavour to pass through the iron. Now in

order that the maximum number of lines of force shall have an iron path for the greatest distance, it is necessary that the inner curved piece of iron shall be rotated into a position where it will form, in conjunction with the outer or fixed iron, the nearest approximation to a complete cylinder. The maximum deflection of the pointer which is carried by the spindle to which the inner piece of iron is attached is consequently obtained when the magnetic circuit formed by the two pieces becomes as good as possible. A section at right angles to the spindle through the middle of the outer sleeve is given separately at A. The outer iron sleeve there shows as if it were a complete cylinder, broken only at the joint, but it will, of course, be gathered from the perspective view that nearer the ends of the sleeve its section would be only a part of a circle. The section also shows the manner in which the small semi-cylinder of iron is attached to the spindle.

The pointer is made of aluminium, and, as shown in the figure it has a small weight attached to it to urge it towards zero on the cessation of the current. In fact, the lifting of this weight is part of the work which the current has to do in deflecting the pointer. It moves in front of an engraved brass-scale plate, which, when used for alternating work, is split from the hole through which the spindle passes, down to the circumference at the bottom of the plate, in order to prevent eddy currents being set up in the plate.

The curvature of the outer iron sheet can be varied, so that the piece with which the inner sheet can be attracted can also be varied correspondingly. This enables the scale to be made to suit the work for which the ammeter or gauge is intended: for instance, an instrument whose range is from, say, 10 to 200 amperes may be required on a circuit where the working current should never rise above 130 nor fall below 90 amperes, and in such a case it might be necessary to measure accurately the value of the current between those limits, while the upper and lower parts of the scale would simply be used to indicate with certainty the fact of the current being either considerably too high or too low. In such an ammeter the outer iron sheet would be so shaped that a given increase in the current strength would move the inner sheet through a much greater distance when near the middle of its path than a similar increase would move it when it is near

either the zero position or the extreme end of its journey. Consequently we should obtain a scale 'open' in the centre and closed at the ends: that is to say, with much larger divisions on the part of the scale where the most accurate measurements are required to be made. The scale could, of course, if required, be made open at the ends and closed in the middle, or, in fact, varied at any part to suit special requirements.

There is one possible source of error with instruments of this description due to the retentivity of the iron, but by exercising great care in the selection and treatment of the metal the error can be practically eliminated. The iron, in fact, is not touched by a tool after it has been annealed, the film of oxide formed during that operation being simply dissolved by immersion in an acid solution.

The coil of the instrument is partly enclosed in a casing of soft iron in order to shield it from external magnetic disturbances, thus rendering the disposition of the leads connected to the terminals a less important matter than would otherwise be the case.

Although it is not so easy to measure accurately a current of several hundred amperes as it is to measure a few amperes or a fraction of an ampere, all these ammeters are calibrated by having their full current passed through them, and its effect, as indicated by the pointer, carefully observed. The required current strength is obtained by means of secondary batteries which are charged in series and joined up in parallel, a definite fraction only of the whole current being measured by the standardising instrument. For example, if it is desired to calibrate an ammeter which is intended to measure currents ranging in strength from 50 to 400 amperes, it is joined in series with the secondary battery and a set of 100 rather stout iron wire resistances, these wires being all joined up in parallel and placed so as to have equal facilities for cooling. A standard ammeter is joined up in circuit with one of these iron wire resistances, and a length of iron wire equal in resistance to the standard instument is removed, so that this composite branch formed of a length of iron wire and the ammeter is equal in resistance to each of the other 99 branches consisting only of iron wire. The main current divides equally

among the 100 branches, and the standard ammeter accurately measures one-hundredth of it, so that for a maximum current of 400 amperes it is necessary to measure only 4 amperes—a comparatively easy matter.

A still simpler and therefore cheaper form of Evershed Gauge is illustrated in fig. 73, in which the cover and scale plate have been removed in order to make the working parts clearer. The coil is clearly shown, and inside this there is a flat disc of very soft iron which is mounted eccentrically on a horizontal spindle. This spindle carries a pointer which moves over the scale and indicates the extent to which the eccentric disc has been raised against the force of gravity by the current circulating in the coil. This portion of the design calls for no further comment if the student has properly grasped all that has so far been said, but there is a further refinement which merits notice. Mounted on the same spindle as the pointer and the disc is a very light arm which carries an exceedingly thin aluminium rectangular vane (corrugated diagonally to impart rigidity). This vane works in a curved brass box of rectangular cross-section just a trifle larger than the vane, so that the vane can move in it without any risk of touching the sides of the box. It should be evident that as the vane is moved the air must squeeze through between it and the sides of the box. This is a device which provides very good 'damping' effects—that is to say, the pointer is prevented from oscillating about the point to which it should be deflected by a given current and very speedily comes to rest in the position

FIG. 73

corresponding to any particular current. In other words, it makes the instrument 'dead-beat.'

As an ammeter has to measure the strength of the current passing through a circuit, it must be so joined up that either the whole of the current shall pass through it and be indicated, or only a definite and pre-determined proportion of the current shall pass through the magnetising coil and a corresponding multiplier used in marking the scale of the instrument. In the former case, thick wire must be employed, otherwise the instrument itself will introduce so much resistance that its insertion in the circuit will reduce the strength of the current. The power, that is the product of E × C, absorbed by an ammeter should be only a very few watts, whence it follows that if we wish to measure a very heavy current the electro-motive force absorbed must be only a small fraction of a volt, and the resistance must be correspondingly small. There is, however, another way of viewing the matter. It has already been shown that the electro-magnetic effect of a solenoid is proportional to the current in amperes multiplied by the number of convolutions, or, to put it shortly, the ampere-turns. If a certain instrument requires 750 ampere-turns in order to give a desired reading, and if the current is 1 ampere, the coil must have 750 turns: if the current is 10 amperes, the coil must have 75 turns; if the current is 1,000 amperes, the coil must have only three-quarters of a turn, and would consist simply of a massive copper cylinder divided on one side, say, by a radial saw cut, the connecting bars to convey the current to and from the instrument being cast with the cylinder and in such positions that the current only travels round the plug for three-quarters of a convolution. Such instruments are, however, inconvenient in a variety of ways, and the introduction of the 'moving coil' instruments led to a small revolution in the construction of ammeters generally. The practice with such instruments is to allow only a portion of the current to pass through the coil of the ammeter, which has a comparatively high resistance, and to join a low resistance shunt across the terminals of the instrument. The result is that an ammeter of any particular make can be constructed with the same type of coil for currents of any strength, and the range of current which the instrument is to measure can be adjusted by

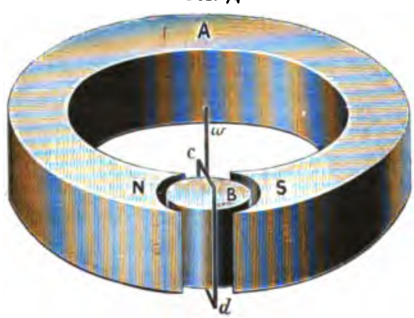
introducing a shunt of suitable resistance. In other words, instead of varying the number of convolutions in the coil, that number remains constant, and the proportion of the current which passes through it is varied. If, for example, an ammeter is provided with such a shunt that it can measure currents up to ten amperes, the same instrument can measure up to 100 amperes, by a corresponding reduction in the resistance of the shunt. These shunts will be more particularly described in the following pages when dealing with moving-coil ammeters.

As there is no permanent magnetic field in a moving iron gauge or ammeter, such instruments can be adapted for measuring alternating as well as direct or continuous currents. In the former case, however, the general tendency is for the readings to be lower than the correct value if the instrument is calibrated to be correct for direct currents, chiefly on account of the 'eddy' currents which are set up in the framework and metal parts in the vicinity of the coil. For instance, it is found that some ammeters of the type under consideration indicate about 2 per cent. lower than the true value of such an alternating current. This error is corrected by permanently shunting the ammeter coil by a smaller coil of copper wire which is overwound with thin iron wire in order to raise its self-induction to the desired value. The resistance of this subsidiary coil is such that it takes 5 per cent. of the total current when the current is a continuous one, and of course the ammeter is calibrated accordingly to indicate the value of the total current. When the instrument is used to measure alternating currents, the shunt coil takes less than 5 per cent. of the total current because its self-induction is greater in proportion to that of the main coil than is its resistance; and the value given to the self-induction of the shunt coil by overwinding it with iron wire as mentioned above, is just enough to reduce its shunting power sufficiently to annul the error of 2 per cent. low reading which would otherwise exist.

We come now to a consideration of the more recent and certainly better class of direct reading ammeters—viz. that which has already been referred to as the 'moving coils' instruments. They are one and all based on the principle which is adopted in the construction of the D'Arsonval galvanometer. In this case

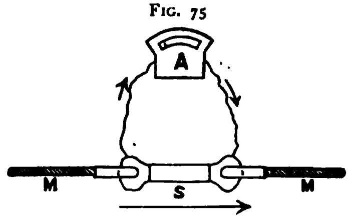
there is a powerful permanent magnet—frequently in the form of a so-called compound magnet, consisting of a number of comparatively thin magnets fixed together with their similar poles adjacent. The magnet is of the horseshoe type, and the two dissimilar poles are brought fairly close to one another. Between them, however, is usually fixed a cylindrical piece of soft iron, the poles of the magnets being bored out, so that there is a small space between these poles and the iron cylinder in which the coil can rotate. Fig. 74 will serve to illustrate the arrangement where N A S represents the magnet or magnets and B the soft iron cylinder. The narrow spaces between the magnet poles and the cylinder will be in such circumstances occupied by a very strong and uniform magnetic field. If the spaces are small and the magnets are even only fairly strong the conditions will be such that external magnetic fields will have little or no effect: that is to say, the strength of the field between the magnet poles and the iron cylinder will be unaffected by the earth's magnetism or by the proximity of other magnetic fields. As a consequence the combination may be used in the presence of powerful dynamo machines of modern construction. The 'coil' *cd* is usually rectangular in shape and embraces, without touching, the cylindrical piece of iron. It is in the type of instrument illustrated in fig. 74, suspended by wires, *w*, which also serve to convey the current to the coil, but, as will be seen later, other means of support for the movable coil have been devised in the construction of ammeters &c. When the current passes through the coil *cd* an electromagnetic field is set up by that coil, and if the coil happens to be in the plane of the lines of force, as it would be if it occupied the diameter connecting the middle portions of the two magnet poles, then the fields due to the magnet and to the coil respectively

FIG. 74



would be at right angles with each other; whence the coil would be rotated until, if the force be sufficient, the lines of force of the two fields would be coincident in direction. This is approximately the position indicated in the figure, but in ordinary practice the instruments are not constructed or arranged so that the current is sufficient to rotate the coil to such an extent. In designing an instrument on these principles, it is evident that unless a very large consumption of power in the instrument itself is to be permitted, the moving coil must be very light. It must, therefore, consist of only a few turns of very fine wire, and will consequently offer considerable resistance and will be incapable of transmitting a heavy current. Such an instrument could not, for the reasons already given, be joined up in a circuit so that the whole current to be measured would pass through it, but the method referred to on page 136 of joining a low resistance in parallel with the instrument can be readily applied. Fig. 75 represents the arrangement, where M M represent portions of the main conductor carrying the full current, and at some convenient point in this circuit a low resistance S is interposed. The ammeter A is connected by comparatively thin wires to the extremities of this resistance S, and consequently the current

FIG. 75



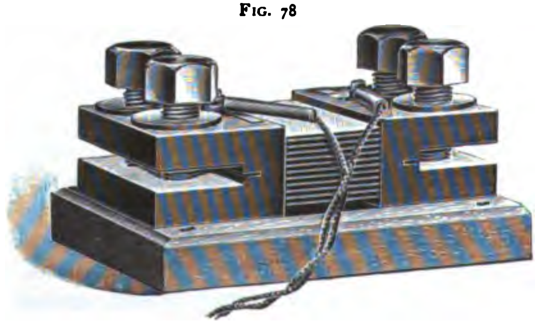
flowing through the ammeter at any moment depends upon the difference of potential at the extremities of S, which difference is directly proportional to the strength of current flowing in the main circuit provided the resistance of S remains unaltered. The resistance S is generally called the 'shunt'; it will be seen that it acts as a shunt to the ammeter, and carries the full main current less the small portion passing through the instrument. It is evident that the shunt must be of sufficient cross-section to carry the full current strength without undue heating, otherwise its resistance would rise with an increase in temperature and the ammeter would indicate a stronger current than that actually flowing.

range of the coil, the distance through which the coil moves on any occasion will be proportional to the current strength, and

FIG. 77

hence the divisions of the scale are uniform. The needle is very accurately balanced, and all parts of the instrument are made to

FIG. 78



gauge, so that they are interchangeable. One of the shunts is illustrated in fig. 78. It consists of a number of strips of platinoid

or other suitable alloy, the ends of the strips being soldered into saw-cuts in the sides of two massive copper blocks mounted on a wooden base. The strips are bare and separated from each other by a small air-space, and the shunt should be fixed on a switch board or in any other convenient position in such a way as to facilitate the passage of air currents through the strips.

The construction of the shunt is therefore such that any heat which will be generated is rapidly dissipated by radiation and convection, and by making the strips of an alloy which has a very low temperature coefficient a shunt is obtained which offers a practically constant resistance, although at different times it may be carrying currents differing considerably in strength. It is important to ensure perfect electrical connection between the shunt and the main conductor, and also between the shunt and the ammeter leads; any resistance due to a bad contact would in the former case cause the ammeter to read too high on account of the development of heat at the faulty contact and the consequent heating of the shunt, while in the latter case the added resistance would cause the ammeter to read too low.

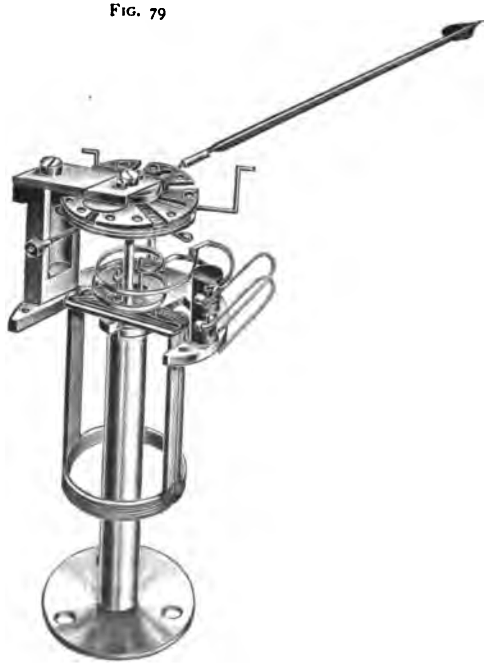
The mains should be securely clamped under the two pairs of bolts which are provided with each shunt. The ammeter leads are permanently connected to the solid blocks. The necessary variation in the resistance of the shunt for instruments of different ranges is effected by varying the width and number of the strips. The resistance of every shunt is such that the difference of potential between the points at which the ammeter is connected will be about 0·06 volt when the shunt is carrying the maximum current which the ammeter will indicate, and every ammeter is calibrated while joined up to its particular shunt, and it must, of course, subsequently be used with this shunt and no other.

In some instances, where the maximum current to be measured is small, the shunt is fixed in the same case as the instrument. When the shunt is separate, the instrument itself can be fixed in any convenient position at any distance from the shunt; but it must be calibrated with these same leads connected, and they must not be subsequently shortened or lengthened without a re-calibration. The distinct advantage which frequently accrues

on account of it being unnecessary to carry the main leads direct to the ammeter can no doubt be appreciated.

The instrument owes its very convenient property of deadbeatness to two causes: first, the moving parts are very light, and hence the motion can readily be arrested; secondly, the copper frame upon which the coil is wound forms a complete electrical circuit of very low resistance in which relatively powerful currents

FIG. 79



are induced by the movement of the coil in the strong field, and these currents, as the student will learn from subsequent chapters, are always in the proper direction to react upon the field so as to tend to stop the motion of the coil, a powerful damping effect being thus produced with every movement. In some instances the frames are made of aluminium, which is lighter than copper, and which gives a sufficiently good damping effect, although its electrical resistance for the same cross-section is higher.

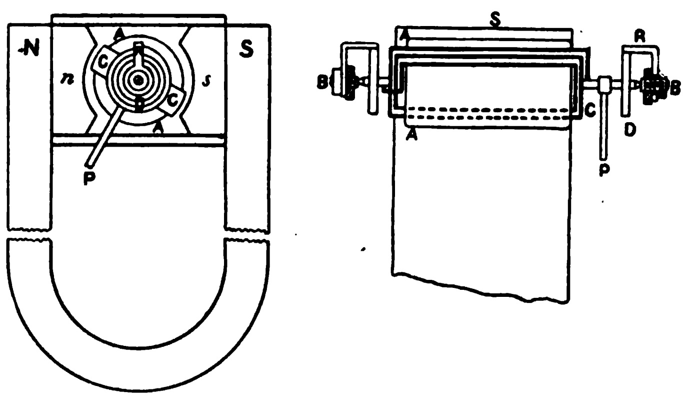
The Evershed moving coil ammeter is based on the same general principles as the Weston, but the coil, instead of being pivoted, is suspended. The coil and the remainder of the moving parts are illustrated in fig. 79. It will be noticed that the coil is so constructed that it does not pass under the iron cylinder, the lower portions of the wire being bent into two semi-circular curves so as to embrace the cylindrical core. There is therefore only one spring against which the current has to act in deflecting the coil, and connection between the coil and the external circuit is effected by means of two very loose spirals of light and springless metal.

FIG. 80

The recording ammeter is a class of instrument which deserves some notice. As the name implies, such an instrument is used for measuring the current, and at the same time registering that current. This is done by substituting for the ordinary pointer a long light arm which carries an inking pen, so that as the current deflects the arm its movement is registered on scaled paper. If the scale were stationary and the current of constant strength, the record would obviously be merely a point, even were the current maintained for hours or days together. It is therefore necessary that the paper should move at a uniform rate, so that if the current were also uniform, the record would be a straight line, the length of which would be directly in proportion to the duration of the current. Fig. 80 gives a general idea of the Kelvin recording instrument (with the front removed), while fig. 81 is a diagram showing the electrical portion in elevation and cross-section. Referring to the latter figure, it will be seen that it is

essentially a moving coil instrument, in which the permanent magnet N S has attached to it two pole-pieces *n s*. Fixed between them is the cylindrical core A A. The moving coil C C is controlled by the spiral spring D, the strength of which can be regulated by shifting the position of the fork R. The coil is pivoted between two jewel screws B B. The pointer or arm carrying the pen is indicated by P. As with all moving coil ammeters, a shunt is provided with special leads connecting it to the coil. The scale or 'chart' upon which the record is to be printed is wound on a drum, and is illustrated in the lower portion of fig. 80. This drum is driven by a well-made clock fitted inside the drum, which

FIG. 81



is arranged to make one revolution in twenty-five hours, the speed of the paper being 0·75″ per hour. This arrangement is made with a view to changing the charts daily, a margin being allowed to avoid the necessity of changing the charts at a particular moment, a necessity which would arise were the drum to complete its revolution in twenty-four hours. The needle is shown in the zero position, but if a current is passed through the instrument the pointer would travel across the chart, the extent of the journey being, of course, determined by the strength of the current. It should be evident that if a current of uniform strength be maintained a continuous straight line would be drawn on the

chart as it revolves. Variations in the current are indicated by the line being zigzagged in accordance with the variations. A handle can be seen on the left side of the figure, and this is provided for lowering the clock-drum for the purpose of renewing the chart, but the act of lowering the drum also winds up the clock for the next twenty-four or twenty-five hours run by means of a rack and pinion provided for the purpose, an automatic release being also fitted so as to render it impossible to over-wind the clock. The instrument requires to be set up in a true vertical position by means of a plumb-bob which is provided in the instrument. The friction between the pen and paper is remarkably small, and

FIG. 82

FIG. 83

with ordinary care in the use of the instrument a very faithful record of the current is the result.

The lineman's detector (fig. 82) is a very handy instrument when used for tracing circuits or localising faults, but it must not be regarded as a measuring instrument. It consists of two ordinary instrument bobbins mounted vertically and wound with two coils of wire, one consisting of a few turns of thick wire and the other of many turns of fine wire. The former is usually wound to 0·2 ohm, and the latter to about 100 ohms. A shunt coil is sometimes added to the thick-wire coil to reduce its sensitiveness. The magnet is about an inch long, and is mounted on a horizontal axis (see fig. 83) so that it can turn freely inside the coils, a long non-

magnetic indicating needle being also fixed on the front end of the spindle and moving over a graduated dial.

One end of each of the coils is connected to one or other of the outer terminals on the top of the case, the other two ends being both joined to the centre terminal. Constructed as described, the needle should be deflected through 40° or 50° by a current flowing through the thin-wire coil, of 10 milliamperes—that is to say, from a single Daniell cell having an internal resistance of 7 ohms. The thick-wire coil should, with the same cell giving a current of 150 milliamperes, cause a deflection of 20° to 30°.

CHAPTER V

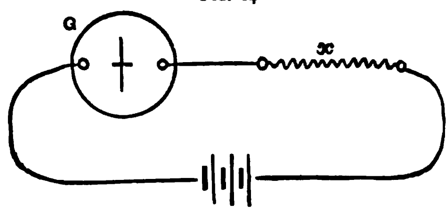
MEASUREMENT OF RESISTANCE

WHEN the difference of potential in volts between the two ends of a wire is known, and also the current in amperes which that difference of potential is able to maintain in the wire, then the resistance of that wire in ohms may easily be calculated, for by Ohm's law it is equal to the number of volts divided by the number of amperes, or $R=\frac{E}{C}$, where E stands for the electro-motive force in volts, C for the current strength in amperes, and R for the resistance in ohms. If, for instance, a difference of potential or an electro-motive force of 15 volts between the two ends of a wire were able to maintain a current of two amperes through it, then its resistance would be $\frac{15}{2}=7 \cdot 5$ ohms. But if the resulting current were only 2 milliamperes, then the resistance would be $\frac{15}{\cdot 002}=7500$ ohms. With one or other of the instruments described in the preceding chapter, the current flowing may be measured, and later on it will be shown how the difference of potential between any two points of a circuit may be measured in volts; and this method is perhaps the best that can be devised for finding the value of very low resistances. But sometimes we know, without the necessity for measurement, the maximum difference of potential or electro-motive force which a certain current generator can produce, and this knowledge will enable us in certain cases to calculate resistance after merely measuring the current strength.

If, for example, we have a battery of which we know the electro-motive force, say 10 volts, and also the internal resistance, say 20^{ω},

we may use it to send a current through the tangent galvanometer, G, and the unknown resistance, x, by joining them all in series as shown in fig. 84. Suppose the resulting current to

FIG. 84



be 20 milliamperes as measured by the galvanometer, then we may find the *total* resistance of the whole circuit by dividing the electro-motive force by the current. The total resistance will be $\frac{E}{C} = \frac{10}{{\cdot}02} = 500^\omega$. Now the resistance of the battery and galvanometer is $20 + 320 = 340^\omega$, and if we subtract this from the total resistance, we get the value of the unknown resistance, x, that is, $500 - 340 = 160^\omega$.

By using the thick wire coils of the galvanometer, and a battery of very low resistance as compared with that of the unknown resistance, no serious error will be made by ignoring the resistance of the battery and galvanometer, and regarding the unknown resistance as the total resistance of the circuit. Under these conditions a number of fairly high resistances may easily be compared, for the same electro-motive force will send through each a current which is inversely proportional to the resistance. Thus, if with three resistances, a, b, c, we get deflections of 30, 25, and 60 tangent divisions respectively, then, $a : b : c :: \frac{1}{30} : \frac{1}{25} : \frac{1}{60}$,

that is, $$a : b : c :: 10 : 12 : 5.$$

Presuming the galvanometer to be so adjusted that a deflection of 30 tangent divisions is obtained when a current of 10 milliamperes is passed through the thick-wire coil, and the battery employed to have an electro-motive force of 2 volts, then the resistance of $a = \frac{2}{0{\cdot}01} = 200^\omega$. Therefore the resistance of $b =$

240°, and of $c = 100°$. As previously stated, however, the resistance of the battery and of the galvanometer must be taken into account, unless they are very low indeed as compared with the resistances which it is desired to measure.

In most of the tests, however, to be subsequently described, it is necessary that a set of resistances whose values are known exactly should be provided. The accuracy of the results obtained depends, in a very great measure, upon the accuracy of the values given to these resistances, so that every care should be exercised in their manufacture, measurement, and use. In Chapter II. some of the principal causes of inaccuracy were enlarged upon, and it was shown how, by avoiding them, a reliable set of resistance coils might be produced.

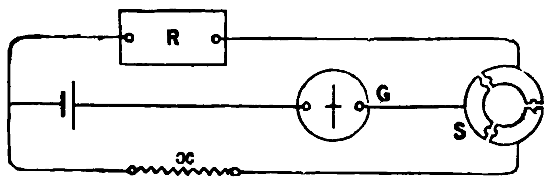
Assuming such a set of coils to be available, let us now discuss its utility in helping us to ascertain the resistance offered by other conductors.

If a wire, whose resistance we desire to ascertain, is joined up with a battery and galvanometer, the current flowing will deflect the galvanometer needle through a certain angle; let this angle be accurately noted. Then, if the unknown resistance is removed from the circuit, and a box of coils of known resistance inserted in its place, this same deflection may be reproduced by varying the amount of resistance introduced by means of the plugs or arms, as described in Chapter II. The current then deflecting the needle will manifestly be exactly the same in strength as in the first case, and therefore (since the electro-motive force of the battery is unaltered) the total resistance of the circuit must be the same as before. Hence the resistance in the box is equal to the unknown resistance. A convenient way of taking this test is shown in fig. 85. R is the set of resistance coils, x the unknown resistance, and S is a three-way plug switch, consisting of three pieces of brass, any two of which may be joined together by inserting a brass plug in the holes provided for the purpose between them. By means of this switch, either x or R may be rapidly placed in circuit, and it is advisable to take a second test after R has been adjusted, to make sure that the electro-motive force of the battery has not been altered by polarisation and so have destroyed the accuracy of the test. The galvanometer, G,

should be a sensitive one; it should, in fact, under all conditions indicate the alteration in the current strength caused by the addition or subtraction of the coil of lowest value in the resistance-box. As by this method the same deflection is reproduced, any form of galvanometer will answer the requirements, providing only that it is sufficiently sensitive. It is not necessary to know the resistance either of the galvanometer or of the battery.

Supposing, however, a tangent galvanometer and a battery, both of very low resistance, to be available, the currents which the battery can send through a known and an unknown resistance can be compared directly by the deflections of the galvanometer needle, for if the deflections are, say, 50 tangent divisions in

FIG. 85



the first case and 45 in the second, and the known resistance is 32 ohms, then

$$45 : 50 :: 32 : x,$$

because the deflection in each case will be inversely proportional to the resistance in circuit. Hence, $x = 35{\cdot}5$ ohms.

When, however, the resistances of the battery and galvanometer are comparatively high, their values must be known or ascertained, and allowed for in accordance with Ohm's law as follows. Let the resistance of the galvanometer, G, be 320^ω, that of the battery $r = 12^\omega$, and the known resistance $R = 560^\omega$; let the current with R in circuit (C_1) give 50 tangent divisions, and the current with x in circuit (C_2) give 45 tangent divisions.

Then, in the first case,

$$C_1 = \frac{E}{R + G + r}, \text{ whence } C_1 (R + G + r) = E,$$

and in the second case,

$$C_2 = \frac{E}{x + G + r}, \text{ whence, also, } C_2 (x + G + r) = E,$$

therefore $$C_2 (x + G + r) = C_1 (R + G + r),$$

whence, by dividing and transposing,

$$x = \frac{C_1}{C_2} (R + G + r) - G - r.$$

Since $\frac{C_1}{C_2}$ is merely a ratio, the strength of the currents in milliamperes need not be known, the number of tangent divisions produced by the currents being inserted instead of C_1 and C_2. Inserting all the values, then, we get

$$x = \frac{50}{45} (560 + 320 + 12) - 320 - 12$$
$$x = 659{\cdot}1 \text{ ohms.}$$

The resistance of the galvanometer is nearly always known and engraved on the instrument, but it is frequently necessary to measure the resistance of the battery at the time of making the test. To avoid this it is better to use a battery of very low resistance, and this in the absence of a suitable battery may usually be obtained by joining up several sets each of comparatively high resistance in parallel.

The equation will then stand:

$$x = \frac{C_1}{C_2} (R + G) - G.$$

By inserting the values as before we can see the amount of the error caused by ignoring the battery resistance of, in this particular case, 12 ohms.

$$x = \frac{50}{45} (560 + 320) - 320$$
$$x = 657{\cdot}\dot{7} \text{ ohms.}$$

The error is thus but 1·3"; and it is not difficult to get a battery of only about 1 ohm resistance to send a sufficiently strong current for the above test, when the error would be negligibly small.

This method also provides us with a means of measuring the resistance of a galvanometer. For, let the second reading be

taken through a known resistance $K = 700^{\omega}$, instead of x, then, ignoring the battery resistance, it follows that, as before,

$$C_1 (R + G) = C_2 (K + G)$$
$$C_1 R + C_1 G = C_2 K + C_2 G$$
$$G (C_1 - C_2) = C_2 K - C_1 R$$
$$G = \frac{C_2 K - C_1 R}{C_1 - C_2}$$

Inserting the values we get

$$G = \frac{45 \times 700 - 50 \times 560}{50 - 45} = 700 \text{ ohms.}$$

With the same apparatus the internal resistance of the battery may be measured. For if the battery is joined up to the low-resistance coil of the galvanometer (three or twelve turns), practically the only resistance in the circuit will be that of the battery x. If possible, the adjustable magnet should be placed so that the deflection is, say, 50 tangent divisions. Now, it will be evident that to *halve* the current flowing, the resistance in the circuit must be *doubled*. If, therefore, resistance R is inserted until the deflection falls from 50 to 25 divisions, the resistance R will be equal to the resistance x of the battery.

Sometimes, however, the effect of the controlling magnet is insufficient to produce a convenient deflection, or it may not be advisable to short-circuit the battery; and it is then necessary to introduce some resistance, say P, in the first test. Then

$$C = \frac{E}{x + P}, \text{ or } C (x + P) = E.$$

If, now, P is increased to R in order to halve the deflection, and therefore halve the current strength,

then $$\frac{C}{2} = \frac{E}{x + R}, \text{ or } \frac{C}{2} (x + R) = E,$$

therefore $$\frac{C}{2} (x + R) = C (x + P),$$

whence $$x = R - 2P.$$

For instance, if with a low-resistance galvanometer it is found necessary to insert 11 ohms in order to bring the deflection down

to 60 divisions, and to increase this resistance to 31 ohms in order to make the deflection 30 divisions, then the resistance of the battery $x = 31 - 22 = 9$ ohms.

In some cases the resistance of a cell is so very low that it becomes a difficult matter to measure it with great accuracy. Secondary cells, especially, have not only a low resistance, but also a comparatively high E.M.F., so that some special method is necessary in dealing with them, if accuracy is desired.

One useful method consists in allowing the cell to send a current through a low external resistance of known value, and then measuring the fall of potential which takes place along this resistance. The fall through the cell can then be found by subtracting the external potential difference measured at the terminals of the cell from the total E.M.F. developed. As the resistance of each portion of the circuit is proportional to the fall of potential taking place along it, the internal resistance of the cell can be deduced. A high resistance voltmeter (see Chapter VI) designed to indicate up to 2·5 or 3 volts is a useful piece of apparatus for this work. The total E.M.F. of the cell can be measured by joining the voltmeter to the cell terminals, because the high resistance of the instrument allows only a feeble current to be generated, so feeble, in fact, that the fall of potential inside the cell is exceedingly low; whence the potential difference indicated is practically equal to the E.M.F. developed. If now a second external conductor, but of low resistance, is also joined to the terminals of the cell, the total external resistance will be considerably reduced, and the fall of potential inside the battery proportionally increased, and a lower pressure will be indicated by the voltmeter, Consequently, if we denote the total E.M.F. by E, the fall of potential in the external and internal portions of the circuit by P and p respectively, the resistance of the cell by r, and of the known external resistance by R, it is evident that

$$E - P = p,$$

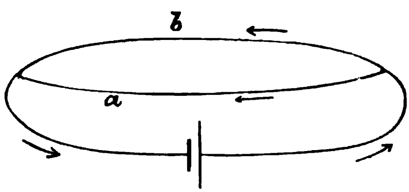
and $$P : p :: R : r,$$

from which we get $$r = \frac{pR}{P}$$

When a battery of such cells is to be measured—say twenty—it is better to reverse nearly half of them—in this case, nine; then the resistance to be measured is that of twenty cells, while the E.M.F. urging a current through them is that of only two cells.

The method next to be described depends upon the fact that if two conductors of exactly equal resistance are joined up 'in parallel' and placed in a circuit, as shown in fig. 86, the current will divide equally between the two—that is, the current in *a* will be exactly equal to the current in *b*. The converse of this holds good, viz. if we have two conductors so joined up in parallel, and we know that the current in *a* is exactly equal to the current in *b*, then we are certain that the resistance of *a* is exactly equal to the resistance of *b*.

FIG. 86



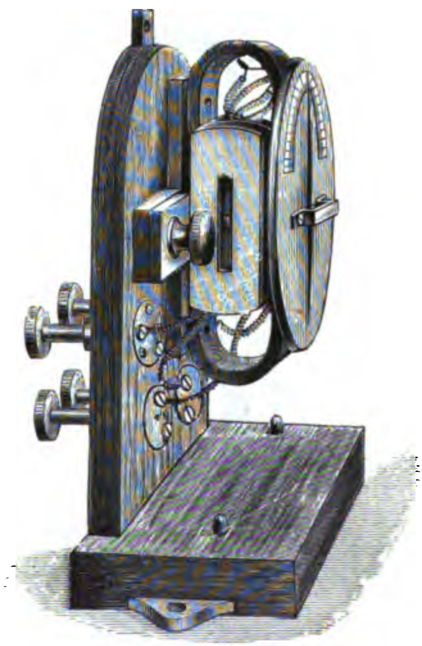
The 'Differential Galvanometer' is an instrument for showing when the currents in two branch circuits are equal. In principle it is very simple. It consists of a magnetic needle, pivoted either horizontally or vertically, surrounded by two distinct coils of wire of exactly equal resistance, and wound so as to act with equal force on the needle. If, therefore, a current is sent through one coil, and a current of equal strength is at the same time sent through the other *in the opposite direction*, their effects will be neutralised one by the other, and the needle will not be deflected. Fig. 87 illustrates, with the cover removed, a good form of differential galvanometer for ordinary work.

The 'needle' is of soft iron and is suspended vertically inside the coils, but its shape and the arrangement for keeping it strongly magnetised are somewhat peculiar.

Fig. 88 shows side and front elevations of the needle and magnets. The spindle, which is pivoted at *a* and *b*, is rather massive, and a piece of brass is inserted obliquely at *c c*, as shown, thus breaking its magnetic continuity. Each half of the needle, *n s*, is fixed at right angles to one half of the spindle at this point, and the whole is embraced by two horseshoe magnets, placed

with their like poles adjacent, as shown in the figure. These magnets form a very strong field in the space in which the spindle lies. A large number of the lines of force pass into the spindle, but when they reach the break in the iron at *c c* they bend upwards through the soft iron needle from one side, and downwards from the other side, the result being that the needle is magnetised with its north pole downwards. On one end of the spindle is fixed a blackened brass pointer, *p p*, which passing over or in front of a circular dial divided into degrees, indicates the movements of the needle. The two wires, each offering, say, 50ω resistance, are wound side by side over two separate bobbins, so that the corresponding portions of each wire are similarly disposed in relation to the needle and exert equal magnetic effects upon it. This method is, of course, far in advance of the old instrument-makers' method of winding one wire alone on one bobbin and the other on another bobbin. The tests for a differential galvanometer are that, if powerful but equal currents are sent in opposite directions through the coils, no effect should be produced upon the needle: each coil used separately should produce equal but opposite deflections with the same current; and the coils should offer exactly the same resistance.

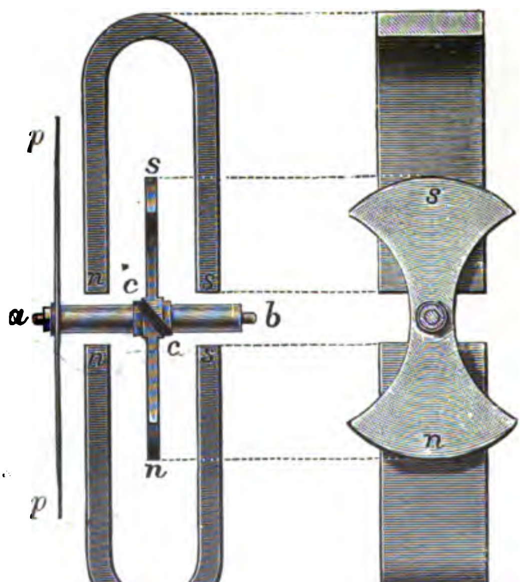
FIG. 87



The inner ends of the two wires on the bobbins are respectively joined together and the other four ends connected to as

many terminals on the back of the instrument. This allows the current to be sent through the coils in several ways. First, through one coil only, the resistance then being 50^{ω}. Secondly, through both coils in series in such a direction that they act upon the needle in the same manner, when the resistance will be 100^{ω} and the deflective action doubled, provided the increase of resistance does not sensibly reduce the current. Thirdly, through both coils in

FIG. 88



parallel and in the same direction; the resistance in this case will be 25^{ω}, and the deflective action, provided the strength of the current in the main circuit remains unaltered, will be the same as that of *one* coil only. Fourthly, through both coils in parallel, but in opposite directions, when the needle should, as already stated, be unaffected. Lastly, through both coils in series in opposite directions, when the needle should also be unaffected. This last

method of joining up is also useful for proving if the deflective effects of the two coils are equal, for the same current passes through each irrespective of their resistance.

Although the wires are wound side by side throughout, it is very rarely that they are found, in making up the instrument, to act with exactly equal force on the needle. There are three ways of attaining this result without affecting the resistance. The position on the bobbins of a portion of either or both of the wires may be altered; or a part of the wire which has the greater effect may be unwound and wound back on the bobbin in the opposite direction; or the stronger may be unwound until an exact balance is obtained, when the length so unwound may be coiled up in the base of the instrument, where, if wound 'double,' it will have no effect on the needle.

The lower half of the needle is made heavier than the upper, to keep it in the vertical position and to assist in restoring it to that position on the cessation of the current; and the current acts against this greater weight when it deflects the needle. The *arm* at which this weight acts increases with the deflection of the needle, so that the angle of deflection cannot be simply proportional to the current strength. The relation between the current and the deflection is, moreover, irregular in consequence of the peculiar shape of the needle, and the proportional deflection diminishes with an augmentation of the current, not only because of the increased effect of the weight, but also because the field due to the current, although almost uniform inside the coil, is far from being so near the edges and just outside.

But at present we shall only consider the use of the instrument with the needle at or near zero, in which position it is most sensitive.

Provided with this instrument, a battery, and a set of resistance coils of sufficient range, we are in a position to measure unknown resistances rapidly.

Fig. 89 shows the best way of making the connections. G is the galvanometer, R a set of resistance coils, x the unknown resistance, and K a key for closing the battery circuit. On depressing the key, the current will divide at a c, the junction of the two coils of the galvanometer, part passing through the coil a b

and R, and the remainder through the oth
to the battery.

Supposing R to be of less resistance th
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consequently the needle will be deflected
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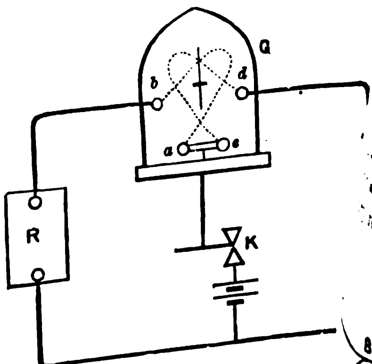
Then the currents flowing through both

FIG. 89



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It may be necessary to
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is P_2.
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potential between any two points is
g, multiplied by the resistance of the
points.
owing in the upper branch, A e B to be C_1,
nch, A f B, to be C_2.

$$P_1 = C_1 \times a;$$
$$P_1 = C_2 \times b;$$
$$C_1 \times a = C_2 \times b;$$
$$\frac{a}{b} = \frac{C_2}{C_1}.$$
$$P_2 = C_1 \times c,$$
$$P_2 = C_2 \times d,$$
$$C_1 \times c = C_2 \times d,$$
$$\frac{c}{d} = \frac{C_2}{C_1}.$$

has also been shown to be equal to $\frac{C_2}{C_1}$;

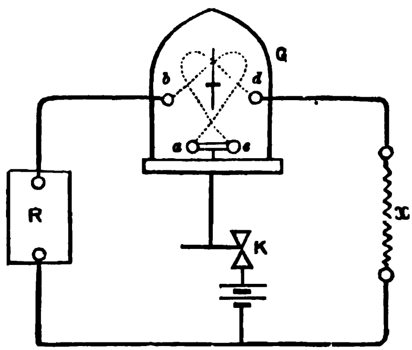
nsequently $$\frac{a}{b} = \frac{c}{d}.$$

This is the relation between the resistances which we sought ...over, and we might, in the same way, prove that it holds ...r cases where the resistances have different values on ... galvanometer connections being made at different

and R, and the remainder through the other coil $c\ d$ and x, back to the battery.

Supposing R to be of less resistance than x, then a greater part of the current will pass through $a\ b$ and R than through $c\ d$ and x; consequently the needle will be deflected to one side. By increasing R this excess of current will be diminished, and the deflection of the needle also decreased, until the needle again stands at zero. Then the currents flowing through both coils of the galvanometer are equal, and therefore the resistance of both branches must be equal: that is to say,

FIG. 89



$$x + 50^{\omega} = R + 50^{\omega},$$

that is, $x = R$.

By further increasing R, the needle would be again deflected, but in the opposite direction to that previously obtained.

Before making a test it is advisable to find out and note in which direction the needle is deflected when R is too large or too small, so that immediately the needle moves to one side or the other we may know whether it is required to decrease or increase R.

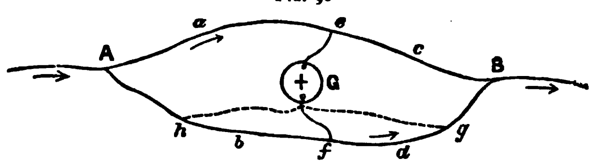
It may be necessary to measure resistances which are either higher or lower than any which can be inserted in the box R. The range can then be extended by shunting one coil of the galvanometer—say, by a wire one-ninth of the resistance of the coil. Then, as only one-tenth of the current in the branch comprising the shunted coil will pass through that coil, a balance will be obtained when the total resistance in that branch is one-tenth of the resistance of the other. For instance, suppose the coil of the galvanometer connected to R to be so shunted, and a balance to be obtained, when the resistance in R amounted to 650^{ω}; then the unknown resistance would be 6500^{ω} nearly. We say nearly, because, in order to obtain a perfectly accurate result, compen-

sating resistance must be inserted to make the resistance of the shunted galvanometer coil equal to 50$^{\omega}$, as explained in the preceding chapter.

In measuring electro-magnets or any single-wound coils, a sudden jerk of the needle, due to self-induction (see Chapter VII.), will always be noticed on making and breaking the circuit. In such cases care should be taken to see that the needle rests at zero when no current is flowing, and then the key should be depressed and the adjustments made with a steady current uninterrupted until the needle again comes to zero.

The differential galvanometer, although a first-rate instrument for comparing two resistances by the equalisation method, loses in simplicity and rapidity when shunts have to be used and allowed for. By means, however, of a piece of apparatus known as the 'Wheatstone Bridge,' the value of almost any ordinary resistance can be

FIG. 90



readily and accurately measured. The principle of this invaluable apparatus is very simple, and is explained by the diagram (fig. 90). Let us suppose two wires, A *a c* B and A *b d* B, either equal or unequal in resistance, to be joined up in parallel and a current sent through or divided between them, as shown in the figure. The current will, as already explained, divide itself between the two wires inversely as their resistances, but, for our present purpose, the current strength is a matter of little or no importance.

If, now, one terminal of a galvanometer, G, is joined to any point, *e*, in one wire, and the other terminal to a point, *g*, in the other, very near to the junction B, a deflection of the galvanometer needle will be observed, indicating a current flowing, say, from *e* to *g*.

On removing the galvanometer wire from *g* and joining it to another point, *h*, also in the second wire, but very near to A, the

galvanometer will again indicate a current, but flowing in the reverse direction, viz. from *h* to *e*. If contact were successively made at points along the wire A *b d* B farther from A, the current would become feebler and feebler until, finally a point, *f*, would be found at which the needle would not be affected at all, showing the absence of a current through the galvanometer.

There can be but one explanation of these experiments. It was clearly laid down and demonstrated in Chapter II. that whenever a current of electricity flows, it invariably does so in virtue of a difference of potential between the extremities of the conductor through which it flows, and, conversely, whenever the extremities of a conductor are at different potentials a current flows through it. These two facts must never be lost sight of, for they constitute the key to a host of electrical phenomena and problems. Inasmuch, then, as it was seen, by the evidence of the galvanometer, G, fig. 90, that a current passed through it when its terminals were connected to the points *e* and *g*, and to the points *e* and *h*, the currents flowed as a consequence of differences of potential between the respective points. And the absence of a current on connecting the points *e* and *f* together is an equally clear proof that those two points were at the same or equal potentials. If we suppose A to be at a higher potential than B, and connect the galvanometer directly to those points, so that it shall share the current arriving at A, the needle will be deflected to one side or the other, the particular deflection being governed by the direction of the current round the needle. Let us suppose the deflection to be to the right. Then, on connecting the galvanometer to A and *g*, or even to *e* and *g*, the deflection will also be to the right, and will establish the fact that the potential at *e* is higher than that at *g*. On the other hand, the opposite deflection which is obtained when the galvanometer is connected to *e* and *h* affords ample proof that the potential at *h* is higher than that at *e*. Now, as the ends of the two wires connected at A are always at the same potential as each other, and, as the ends at B are also at the same potential as each other, although lower than at A, it follows that the fall of potential along A *a c* B must equal that along A *b d* B. It also follows that if we fix upon any one point in either of the wires, there must always be a point somewhere in the other wire which will be at

exactly the same potential, and if these two points are connected together no current can possibly flow between them. Herein is the underlying principle of the Wheatstone bridge.

We must now endeavour to discover what relation, if any, exists between the resistances of the four sections into which these wires are thus experimentally divided. Let the resistance of the section between A and e be denoted by a, that between A and f by b, between e and B by c, and between f and B by d.

The difference of potential between A and e is equal to that between A and f; call this P_1.

Again, the difference of potential between e and B is equal to that between f and B; call this P_2.

Now we have seen that in every case (since by Ohm's law $E = C\ R$) the difference of potential between any two points is equal to the current flowing, multiplied by the resistance of the conductor between those points.

Suppose the current flowing in the upper branch, A e B to be C_1, and that in the lower branch, A f B, to be C_2.

Then $$P_1 = C_1 \times a;$$
also $$P_1 = C_2 \times b;$$
therefore $$C_1 \times a = C_2 \times b;$$
or $$\frac{a}{b} = \frac{C_2}{C_1}.$$
Again, $$P_2 = C_1 \times c,$$
also, $$P_2 = C_2 \times d,$$
therefore $$C_1 \times c = C_2 \times d,$$
or $$\frac{c}{d} = \frac{C_2}{C_1}.$$

But $\frac{a}{b}$ has also been shown to be equal to $\frac{C_2}{C_1}$;

consequently $$\frac{a}{b} = \frac{c}{d}.$$

This is the relation between the resistances which we sought to discover, and we might, in the same way, prove that it holds good for other cases where the resistances have different values on account of the galvanometer connections being made at different points.

The relation may also be viewed from another standpoint. The fall of potential along a conductor is proportional to its resistance, and, conversely, the resistance of a conductor is proportional to the fall of potential which takes place along it. Now, the total fall of potential along the two branches (fig. 90) is equal in amount, and the potential at e is equal to that at f; and the fall along a is equal to the fall along b, and also the fall taking place along c is equal to that along d. Therefore the value of the resistance a bears to that of c the same ratio as does b to d, that is

$$a : c :: b : d,$$

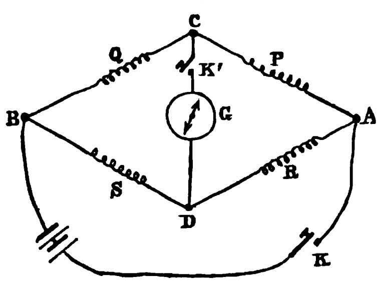
and therefore also $$a : b :: c : d.$$

If one of these resistances, say c, were unknown, and the other three known, we could readily determine the value of c, for $c = \frac{ad}{b}$.

This is, in fact, the method by which resistance is measured with the Wheatstone bridge.

We have in practice four resistances, P Q R S, one of which say P, is unknown and the others known, joined up as in fig. 91. The junctions at A and B are maintained at different potentials by means of a suitable battery, but the galvanometer is permanently connected to the other junctions, C and D, and instead of varying the position of the galvanometer connection, D, the known resistances Q R S are varied and adjusted, until the absence of a current through the galvanometer proves C, the junction of P and Q, to be at the same potential as D, the junction of R and S. The value of P can then be calculated, as above, the simplest case being when Q = S, for then P = R. Two keys, K and K′, are provided for the purpose of joining up or disconnecting the battery and galvanometer circuits respectively.

FIG. 91

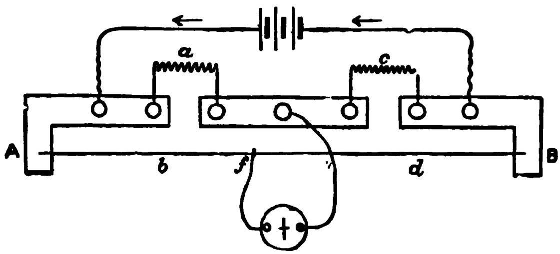


There are various ways of performing the necessary adjust-

ment of the known resistances; but a very good form of bridge for measuring low resistances may be constructed upon the principle illustrated in fig. 90, where the point of equilibrium was found by shifting one of the wires connected to the galvanometer along A *b* *d* B, thus varying the *ratio* of the resistances *b* and *d*.

Three brass or copper strips, so stout as to have practically no resistance, are fixed on to a mahogany board, as in fig. 92. Between the ends of two of these strips a wire, A B, is stretched. It is convenient to have this wire one metre in length, with a scale placed under it, divided into a thousand parts. There are three terminal screws on the middle strip, and two on each of the others. The unknown resistance, *c*, is connected to the two adjacent ends

FIG. 92



of the middle and right-hand strips, while a known resistance, *a*, is joined to the adjacent ends of the middle and left-hand strips. A battery is joined up to the outside strips, and a current can thus be sent through the branch *a* and *c*, and the branch *b* and *d*, in parallel. One end of the galvanometer coil is joined to the terminal screw at the junction of *a* and *c*, where the potential will have fallen to a certain amount. The other end is connected to a slider which passes along over the wire *b* *d*, and which, when pressed down, makes contact with the wire, and allows the exact point at which contact is made to be read on the metre scale. As previously explained, a point, *f*, is sought for, at which, contact being made, no current flows through the galvanometer. Then $c = \frac{d}{b} \times a$. It is clear from this equation that $\frac{d}{b}$ is merely a ratio,

and need not be known in ohms. If the wire A B is of uniform resistance throughout, it is sufficient to know the length in millimetres of b, and the length in millimetres of d; but the resistance of a must be known in ohms. Supposing a were 2·5 ohms, and a balance to be obtained with the slider at a point 440 millimetres, from A; then $b = 440$, and $d = 560$. Therefore $c = \frac{560}{440} \times 2{\cdot}5$ $= 3{\cdot}1\dot{8}$ ohms.

The stretched wire must be of considerable resistance so as to make the fall of potential per unit of length appreciable, and it should be of some hard durable metal, otherwise it would become worn by the slider and its uniformity of resistance destroyed. For these reasons the wire should be made of German silver, platinum silver, or platinoid. A key should be inserted in the battery circuit, to prevent the current being kept on longer than necessary and heating the wires. Extra resistance in the galvanometer or battery circuits introduces no error, merely reducing the sensitiveness of the arrangement, but it is important to secure good clean connections in the other branches, as any resistance introduced there might cause a great error in the result. To obtain the best results the resistance of the battery should be rather low, and its E.M.F. comparatively high; the resistances in the arms of the bridge should not differ very greatly; and the galvanometer must, of course, be sufficiently delicate to indicate the difference of potential caused by moving the slider through the shortest measurable distance. But the length of the wire on the galvanometer must not be indefinitely increased to attain this result, otherwise the resistance so added reduces the current in a greater proportion than the deflective effect is increased.

There is, in fact, for every separate test, a certain resistance which it would be best to give the galvanometer. In practice, however, we can do no more than wind the galvanometer in such a manner as will make it best suited to the average conditions under which it will be employed. For an ordinary slide-wire bridge the galvanometer resistance should not greatly exceed one ohm.

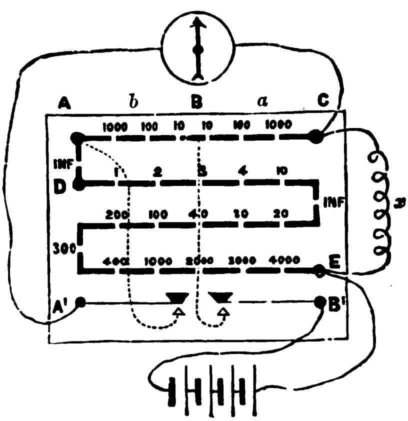
The slide-wire bridge answers well in a laboratory, where it is exceedingly valuable for measuring low resistances. A more

practical form of the Wheatstone bridge, and one which is very largely used for general work, is shown in fig. 93, and its connections in fig. 94.

FIG 93

There is no exposed stretched wire here, but all the resistances are placed in a mahogany box with an ebonite top, their ends being connected to brass blocks fitted with plugs, as in the case of any ordinary resistance-box. These resistance coils are measured with extreme care, and the value of each in ohms is marked upon the ebonite. Double terminal screws are employed to avoid the risk of resistance being introduced by the careless connection of two wires on to one terminal. In the general view it will be seen that there are two keys, each, when depressed, making contact with a metal stud; these keys are marked A′ and B′ in fig. 94. A terminal screw is connected to each key, and to the right-hand one is joined the zinc pole of the testing battery. The stud under this key is connected beneath the ebonite cover to the brass block B in the middle of the back row of resistances, so that the zinc pole of the battery is joined to this block when the right-hand key is depressed. It is at this point then,

FIG. 94



corresponding to B, the junction of Q and S in fig. 91, that the current divides, and on either side are three coils of 10, 100, and 1000 ohms respectively, any or all of which can be inserted at pleasure. At each end of this row of coils is a terminal screw, and the galvanometer is connected to these points. But, as we have seen, it is necessary to have a key in the galvanometer circuit, and it is very convenient to place both keys close together in the front of the instrument, as shown. One wire from the galvanometer is therefore brought to terminal A′—that is, to the left-hand key—and the stud under this key is connected to terminal A, as shown by the dotted line. Therefore, when A′ is depressed, this side of the galvanometer is joined to terminal A. The other side of the galvanometer goes direct to the double terminal C. The two 'arms' of the bridge B A and B C correspond to the arms *b* and *a* in fig. 90, and to S and Q in fig. 91, and the arm marked R in the latter figure here consists of a number of coils, ranging from 1 ohm to 4000 ohms, placed between the terminals D and E. We have thus three arms of the bridge of known values, and the fourth, or unknown resistance, *x*, is placed between terminals C and E. The copper pole of the battery is brought direct to terminal E, which corresponds to the junction of P and R in fig. 91. Between the arms B A and D E—that is, between the terminals A and D—is a space marked 'infinity.' There is no coil connected to the two blocks at this point, so that the resistance is infinite: that is, the circuit is disconnected, when the plug is removed. This arrangement is exceedingly useful, for it is possible to increase the range of measurement considerably, by removing the plug and inserting an extra box of coils in the circuit here; and further, it is often convenient, in some tests, to be able to separate the coils into two independent sets. There is a second 'infinity plug' between the 10 and 20 ohm coils, and when using the apparatus simply as a set of resistance coils these plugs may be used as keys for disconnecting or joining up the circuit. But this second plug is also useful when employing the bridge in the orthodox fashion. Let it be supposed that it is impossible, by any manipulation of the coils, to establish a balance. Then if a balance is established by removing the infinity plug, it is proved that there is a disconnec-

tion in the arm x, or if the deflection obtained is very feeble, it may be taken that the resistance in x is 'above bridge,' or too high to be balanced.

Let us suppose, however, that the bridge has been properly joined up, with an unknown resistance x, the value of which it is desired to find, between C and E.

It is clear that A and C are the points which we want, by adjusting the various resistances, to bring to the same potential, and the galvanometer is connected to these points so as to indicate when this result is attained. We begin by inserting some resistance in the arms B A and B C: say, 100 ohms in each. These resistances are not again altered during the measurement, but the adjustment is made by varying the amount of resistance in the arm D E until the galvanometer shows that a balance has been obtained. When this happens the value of the unknown resistance, x, is equal to the amount which has been inserted in the arm D E. Much time may be saved and greater accuracy ensured by taking a test methodically, and the following points should be attended to. Before starting it should be ascertained that the plugs are firmly in their places and that all the connections at the terminals are good, and to ensure this it is advisable to take advantage of the double terminals provided, and place only one wire on each screw. The galvanometer having been placed in a position convenient for the experimenter, some coils in each of the three arms must be put into circuit, the amount in the arms D E being made as near the unknown resistance as can be guessed. The right-hand key should be depressed and then, a moment afterwards, the left-hand key, and the galvanometer observed; probably the latter will indicate the passage of a current, and it should always be found which way the needle moves when the resistance in the arm D E is, say, too high. If that is done, one can see, immediately the needle moves, whether it is necessary to increase or reduce the resistance in D E in order to get a balance. This is much quicker than obtaining the balance at random. The galvanometer key must only be lightly tapped so as to just indicate in which direction the resistance must be varied until a balance is nearly obtained, when it may be held down for a longer period. This prevents a heavy current being passed through the

galvanometer; and the student will hardly require to be warned that if the battery is kept on too long the bridge coils will become more or less heated and their resistance varied. It should also be borne in mind that with a very delicately made galvanometer a suddenly applied heavy current is likely to injure the needle or the pivot.

We considered above the simple case when the resistances of the arms B A, B C were equal, but the bridge is not always used under these conditions.

If, for instance, the unknown resistance is comparatively low and we desire to measure it to within a fraction of an ohm it is then necessary to have these arms of unequal resistance; we should make B A, say, 100 ohms and B C 10 ohms. Then, if a balance were obtained with 13 ohms in D E, x would be equal to 1·3 ohm. For, by the principle of the bridge,

$$x = \frac{BC \times DE}{BA} = \frac{10 \times 13}{100} = 1{\cdot}3.$$

And by using 1000 ohms in B A and 10 in B C, measurements to within $\frac{1}{100}$ of an ohm might be made.

When the unknown resistance is very high, then the ratio must be reversed, taking, say, 10 in B A, and 1000" in B C. If, now, a balance is obtained with 1309 ohms in D E, then

$$x = \frac{1000}{10} \times 1309 = 130900 \text{ ohms.}$$

When using this ratio it is not always possible to obtain a perfect balance and so determine the unknown resistance exactly, because the lowest unit in the arm D E is 1 ohm, and this is equivalent to 100 ohms in the unknown resistance. For instance, if in the last test the unknown resistance were 130,925 ohms, it would be necessary to increase the resistance in D E by a quarter of an ohm in order to get a perfect balance, and this fraction is not at our disposal. A supplementary set of resistances having fractional values may be inserted between the terminals A and D, provided that the arrangement is sufficiently sensitive for the galvanometer to respond to the change produced by these fractions of an ohm; but for

general work it is sufficient to know the value of a very high resistance to within 10 or 20 ohms, and this can always be estimated by observing the movements of the needle when the resistance in D E is less than 1 ohm too high and less than 1 ohm too low. It will be seen that the range of the bridge without supplementary resistance is such that any resistance between 0·01ω and 1,111,000ω can be measured.

It may be remarked that the efficiency of the Wheatstone bridge is frequently reduced by the injudicious choice of a battery. The point to be borne in mind is, that a considerable fall of potential is necessary along the arms of the bridge—that is, between the points A and B in fig. 90. The greater the difference of potential between these points, the greater will be the effect on the galvanometer needle for a given change in any of the resistances, and therefore the higher the degree of accuracy to which we can measure. Now, suppose the bridge to be of the slide-wire form, and the resistance of the arms between A and B to be 2 ohms. If we employ a battery of 10 Daniell cells, having a resistance of 5 ohms per cell, the potential difference between A and B will be considerably less than three-quarters of a volt, all the rest of the fall taking place inside the battery. A single Grove cell, having a resistance of ·2ω, could maintain about 1·8 volt under similar conditions, although its E.M.F. is only one-fifth of that of the Daniell battery. This clearly shows the effect of excessive resistance in the battery, and it is evident that when the resistances in the bridge are low, the battery employed, while having a sufficiently high E.M.F., must have a very low internal resistance. When, however, the resistances are high, resistance in the battery circuit is not so harmful (as the fall of potential in any part of a circuit is directly proportional to the resistance of that part), and a battery of Daniell cells may with advantage be employed; for, as a rule, the internal resistance of a battery of Daniell cells is so high, that even when short-circuited the current is but a fraction of an ampere. But the E.M.F. of the battery is often kept unnecessarily low to avoid a strong current heating the coils; there is, of course, a limit, but by a skilful manipulation of the keys provided, the time during which the current need be kept on is so very short that the heating is inappreciable.

We have remarked that it is better to depress the battery key first, and allow the current to become steady before tapping the left-hand key and throwing the galvanometer in circuit. A very short time is sufficient for this, but extra care should be taken that it is done when the unknown resistance is an electro-magnet, or any coil which is liable to the phenomenon of 'self-induction' (see Chapter VII), or when it has any 'electrostatic capacity,' as in the case of a long open line or more particularly of a cable, otherwise the needle will move violently, although the actual resistance may be truly balanced. To enable the student to understand how the nature of the resistance can cause the potential at any two points to be widely different when the current is starting or stopping, and yet equal when it is steady, we may employ an analogy. Suppose we have two equal iron water-pipes joined up as in fig. 90, with some piece of apparatus to indicate a difference or equality of pressure, in the place of the galvanometer, the points *e* and *f* being at equal distances from A or B. Then, the pipes being equal in all respects, the pressure at *e* will always be equal to that at *f*, no matter how the difference of pressure at A and B may be varied. If, now, one branch, A *f* B, is replaced by a very flexible indiarubber pipe of similar dimensions, this no longer holds good. Suppose the pipes to be empty and then water at a high pressure to be forced in at A; the pressure at *e* will rise quicker than at *f* because the flexible pipe expands, and this occupies a short time. When the expansion has reached its limit the pressures at *e* and *f* are equal, but on suddenly stopping the flow at A, the pressure at *f* remains higher than at *e* for a brief moment owing to the contraction of the pipe.

Somewhat similarly, as we shall see later on, a current of electricity can never rise to its full value, nor die away, instantaneously; for this reason, the coils of the bridge are double wound so that in them the rise or fall is very rapid, and when the unknown resistance is such that the rise or fall takes place at a different rate, the current must be allowed to become steady before the second key is closed.

The peculiar method of winding the bridge coils is also useful in preventing any direct action, which might be caused by the current circulating in them, being produced upon the galvano-

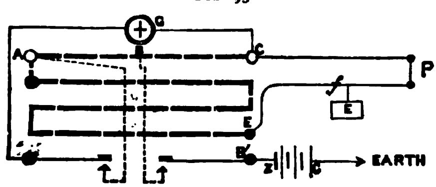
meter needle. When an electro-magnet is being measured, the galvanometer must be placed far enough away to avoid its being affected when the current is passed through the electro-magnet. When there is any reason to suppose that some such effect as this exists, the battery key should be closed and opened several times, the galvanometer key being left open and the needle watched. If it moves at all, we have proof positive that some portion of the apparatus is producing a disturbing effect upon the galvanometer.

When both ends of the unknown resistance are not easily accessible—that is to say, when it is impracticable to bring both ends of the conductor to the bridge—the test may be made by joining one end to the terminal C, and connecting the distant end to earth. The terminal E—that is, the junction of the arm D E with the copper pole of the battery—should also be put to earth, and then the test can be made in the usual manner, because the two earth-connected points are at the same potential, and behave in precisely the same way that they would if they were joined to a common terminal.

A leakage sometimes occurs in a covered wire or cable, which allows more or less of the current to escape to earth, provided some other point of the system is also earthed. It is necessary to be able to determine the exact position of such a 'fault,' or point of leakage, and this might easily be done by disconnecting the line beyond it, and then, treating the fault as an earth, measuring the resistance of the wire up to this earth as described above. It rarely happens, however, that any fault develops which does not offer considerable resistance to the passage of the current to earth, and as the amount of this resistance is never known it cannot be allowed for. Further, the resistance at the fault frequently varies so rapidly that it is not possible to obtain a balance at all, and some different arrangement of the bridge is therefore necessary. We have seen that in the battery circuit extra resistance, and even variable resistance, causes no error in the result, although it reduces the sensitiveness of the bridge; and if this variable earth-fault can be placed in the battery circuit, we can ignore its resistance altogether. This can readily be done if both ends of the wire are accessible; if not, it is necessary to have a second or return wire, and connect the distant ends of

the two together. This arrangement is known as the 'Loop test,' and is illustrated in fig. 95. The copper pole of the battery is put to earth, the zinc pole being always joined to line in fault-testing, as the current in that direction—usually by an electrolytic effect—decreases the resistance of the fault and so makes it more pronounced. E P is the faulty wire, the fault being shown at *f*. C P is the sound wire by means of which we reach the other end of the faulty wire, the two being looped together at P. The good wire must be joined to terminal C, and the faulty one to E. On depressing the battery key the current flows through the bridge and the lines, finding earth at the fault, and a balance can be obtained in the usual way. Let R be the resistance inserted in A E, and let x represent the unknown resistance of the faulty wire from E to the fault at *f*. Then the total resistance of this arm of the bridge is $R + x$. The other arm consists of the sound wire, C P, and that portion of the faulty wire from P to *f*. Let the total resistance of this arm be called y. Let a be the resistance in B C, and b that in B A, then

FIG. 95



$$a : y :: b : R + x,$$

that is
$$y = \frac{a}{b} \times (R + x) \quad . \quad . \quad (1).$$

We have here two unknown quantities, x and y, and must therefore get a second simple equation in order to eliminate one of them. It is clear that the total resistance of the two lines is $x + y$, and usually this is known; if not, it can be measured by joining up the bridge in the ordinary way (that is, connecting the copper pole of the battery to terminal E), and measuring the resistance of the loop as that of a single wire without fault; for there will then be no leakage at the fault, as no other part of the system is earthed. Suppose the resistance thus found to be L ohms, then

$$x + y = L;$$

therefore
$$y = L - x \quad . \quad . \quad (2).$$

Therefore, from equations (1) and (2),

$$\frac{a}{b} \times (R + x) = L - x;$$

therefore $$x = \frac{bL - aR}{a + b}.$$

If we make $a = b$, as is frequently done in this test, then, evidently,

$$R + x = L - x,$$

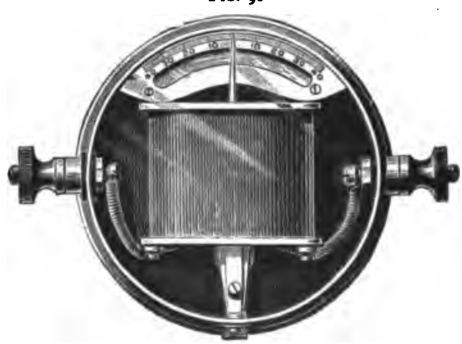
and $$x = \frac{L - R}{2};$$

or, we simply subtract the resistance in A E from that of the two lines, and, dividing by 2, obtain the value of x.

Now, x is the resistance in ohms from E to the fault; the length of the wire E P is known, and therefore its resistance per mile, or any other unit of length, is known. Thus we can at once ascertain the distance of the fault in miles or yards by dividing x by the resistance per mile or per yard as the case may be.

The galvanometer generally used with the form of bridge above described has a resistance of 800 ohms; it is shown in fig. 96, and is a very good instrument—portable, yet capable of giving evidence of a very small potential difference. When joined up in circuit with a resistance of 20,000 ohms, and a single Daniell cell (the current then being about one twenty-thousandth of an ampere), it will give a deflection of 25°.

FIG. 96



The coil consists of many turns of fine silk-covered wire, wound on a single brass bobbin. The needle, which is pivoted, lies exactly in the centre of the coil, and is quite covered by it. At right angles to the needle is fixed a pointer, which projects from the coil, and, passing over a scale and a strip of looking-glass, indicates the slightest movement of the

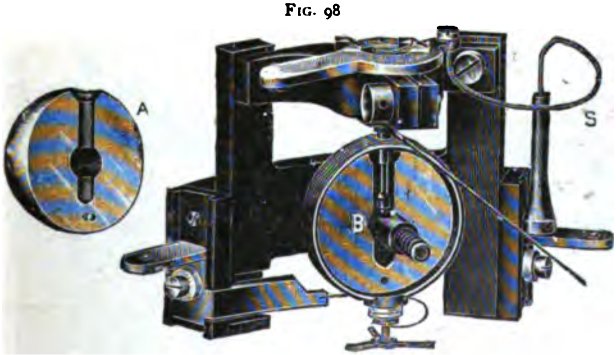
needle. A lever is provided for lifting the needle from its pivot when not in use, and each end of the coil is connected to a terminal which is insulated from the brass casing by ebonite. The features in the design of the instrument which enable it to respond to very feeble currents are the great length of wire employed, the nearness of this wire to the needle, and the excellent pivoting of the needle, which allows it to move easily.

Mr. Paul has constructed a galvanometer of extreme sensitiveness, which is therefore very suitable for use with the Wheatstone bridge. It is designed on the moving coil principle and is illustrated in fig. 97. The field is maintained by a strong circular magnet M M, and the instrument is therefore independent of the proximity of other magnets or electro-magnetic fields. This is in itself a great advantage, as it permits of the bridge being used in the vicinity of dynamos, motors, etc. The moving coil and its attachments are illustrated separately on an enlarged scale in fig. 98. The coil encircles a spherical soft iron core, which is made in two hemispherical pieces. One of these pieces is shown separately at A. The other piece B is shown in position and enveloped by the coil, which is mounted on a single pivot. This pivot is situated in the geometrical centre of the core so that the instrument does not need levelling, for if it is placed a few degrees out of level the coil retains its vertical position and is still concentric with the core. This arrangement has also the advantage that the coil can be raised off its pivot when the instrument is out of use, and automatically restored when required. This is accomplished by the introduction of a plunger which protrudes through the bottom of the case, so that when the instrument is placed on a table or other approximately level surface it is pressed upwards and lifts one end of a lever, the other end of which, tipped by a light spring, drops gradually and lowers the coil on to its bearing. When the instru-

FIG. 97

ment is raised, or is placed in its case, the plunger falls back and the coil is raised off its bearing. The coil is kept in its normal position by means of a controlling spring in the form of a helix, to which is attached a fitting which may be rotated by means of the spring S to set the indicating needle to zero. The coil is wound on a light steel frame or 'former,' which is fitted with a vertical brass spindle carrying the pivot. This pivot when the instrument is in use rests on a finely jewelled bearing which is fitted in a recess in the horizontal cock-piece shown protruding from the centre of the hemisphere B. This cock-piece also carries a stud for holding the two hemispheres together. The resistance of the instrument is

FIG. 98



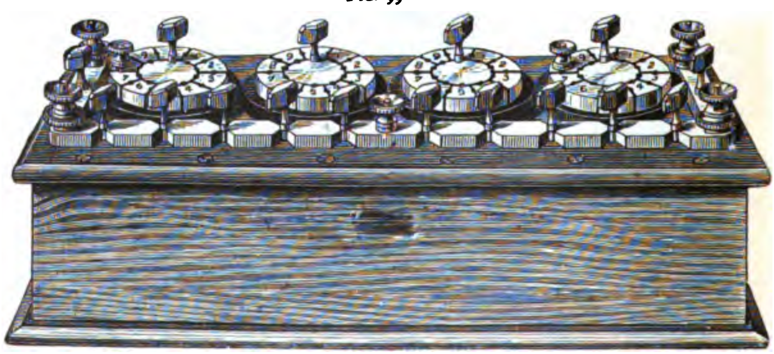
210$^{\omega}$ and its sensitiveness is such that one degree of deflection is produced by a current of 0·000001 ampere.

Another form of Wheatstone bridge is shown in fig. 99. This has a very great range, and some of its coils are joined up differently from those in the apparatus last described.

The two 'ratio arms' consist each of five coils, of 1, 10, 100, 1000, and 10,000 ohms resistance, and are connected up in the usual manner. The arm which is varied in balancing is divided into four sets of coils, each set consisting of nine *equal* coils. The resistance of each coil in the first set is 1$^{\omega}$, in the second 10$^{\omega}$, in the third 100$^{\omega}$, and in the fourth 1000$^{\omega}$. Sometimes a fifth set of ·1$^{\omega}$ each is added. In the figure will be seen four sets of 10 brass blocks surrounding a circular central one, with which they can be

separately connected by a plug. The block partly hidden by the plug is numbered 0, and this block is connected to the centre of the next dial. Between each two of these numbered blocks (except between 9 and 0) one of the equal resistance coils is placed, and by means of the plug any number of them can be brought into circuit. For instance, if the block numbered 5 is so joined to the centre plate, the current passes from the plate by means of the plug, and through five of the coils round to the block number 0, which is joined to the next centre plate, or, in the case of the last dial, to a terminal screw. Some tests can be very quickly made with this form of bridge, and the result seen at a glance, and an advantage results from the fact that only a few and invariable

FIG. 99



number of plugs are brought into use, thus reducing the liability to error due to a varying resistance between the plugs and the faces of the brass blocks. Of course, as only one plug is used for each dial, the circuit is disconnected in the variable arm every time a plug is shifted. In order to obtain the full advantage of the very great range of this particular bridge, it is necessary to use a galvanometer even more sensitive than that illustrated in fig. 96, and some form of 'reflecting' galvanometer is usually adopted. In a reflecting galvanometer a small magnetic needle suspended by a single fibre of silk is placed inside a coil of wire, and as the needle itself is hidden from view its movements are indicated by a beam of light. A small circular mirror is cemented to the needle

and moves with it, and a beam of light thrown on to this mirror is reflected on to a suitable scale; the spot thus projected on the scale indicates and magnifies the movements of the needle.

One of the most important uses to which the instruments and methods described in this chapter can be applied is that of determining the 'insulation resistance' of an electrical circuit—for example, an electric-light circuit—which is accomplished by entirely disconnecting the remote ends of the conductors, and then measuring the resistance offered by the insulating material to the leakage of the current from one conductor to another, or to earth. Should this resistance fall below a certain pre-arranged standard, evidence will be afforded of the existence of a fault which requires to be localised and removed forthwith. The insulation of the conductors having been proved, the switches and other fittings may then be joined up, when a second careful test should be made, which in most cases will reveal the fact that the insulation resistance has fallen considerably, often as much as 50 per cent., due mainly to surface leakage. By testing the insulation resistance of the conductors separately a ready means is afforded of determining whether a particular fault is in the covering of the wire or in the fittings, and it may be observed that a certain amount of leakage at the fittings should be deemed of less importance than an equal or even a smaller leakage in the conductor covering; for whereas in the former case it is mostly due to moisture, and therefore not usually liable to any serious increase, in the latter case it indicates a damaged or inferior insulating material, a fault which will most assuredly develop under the continued electrical stress.

In electric-light or power installations very heavy currents and rather high E.M.F.'s are frequently employed, which might cause serious damage to life and property should the insulation at any point be allowed to fall below a certain standard or become in any way faulty, and any such fault would, of course, also impair the efficiency of the system. Similar conditions obtain with any system of electrical conductors and fittings for any purpose whatever, and it is necessary that some convenient means should be available for efficiently testing the whole installation under conditions equally as trying as the maximum stress which it will be called upon to sustain in practice. Especially should the

source of electrical power employed for the test be able to develop an E.M.F. at least equal to the maximum intended to be used, otherwise there will be considerable risk that small incipient faults will not be shown up during the test, and will only become manifest when the circuit is in practical use, and when, therefore, the greatest inconvenience, and possibly damage also, will result.

As 100 volts is the lowest E.M.F. which generally obtains in practice, and which is therefore the lowest E.M.F. which should be employed in insulation testing operations, it is evident that the employment of ordinary batteries for such a purpose would be exceedingly inconvenient, although since the advent of the dry cell, a large number can be packed into a very small compass, and there is, of course, no fear of liquids spilling or of other similar trouble arising. A small magneto machine, such as we shall describe in a subsequent chapter, is, however, far more convenient and portable, but it is hardly suitable for use with the apparatus ordinarily constructed, such as the Wheatstone bridge, for the measurement of resistance. The Evershed 'Ohmmeter' is an instrument which is designed to work with such a machine. It is called an 'ohmmeter' from the fact that its pointer indicates directly the number of ohms or megohms in the resistance under measurement. In practice, however, one does not actually require to find the exact insulation resistance of an installation within a few ohms more or less. It is not possible to measure the higher resistances by means of an ohmmeter with certainty to within 100 ohms or so, but this is immaterial, as, if the insulation is below the standard, it matters little whether it happens to be, say, 700,000 or 700,200 ohms. It is, indeed, sufficient if the apparatus can assure us whether, under the stress produced by a sufficiently high E.M.F., the insulation is above or below a certain standard, which we may here suppose to be fixed at 1 megohm. The apparatus under consideration can promptly and decidedly indicate whether the resistance is above 1 megohm or below it, and supposing it to be above, the installation may be passed as satisfactory; but if below this standard, the circuit should be tested in sections until the fault has been localised.

In the original type of ohmmeter the generator was fixed in a separate box, while the indicator or the ohmmeter proper was

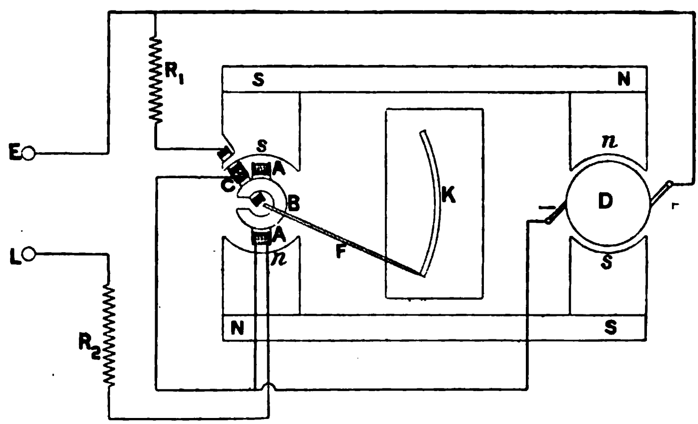
placed in another. In its present form the generator and ohmmeter are enclosed in one box. The remarkable unanimity with which instrument makers have, in the construction of their more accurate apparatus, resorted to the principle of the moving coil galvanometer has been manifested in the design of the later form of Evershed's ohmmeter, which is known as the Megger. It is certainly a considerable advance upon its prototype, not the least important feature being that the range of the instrument reaches

FIG. 100

to 2000 megohms, as against a maximum of 50 megohms with the older pattern, while the E.M.F. has been increased from a maximum of about 120 volts in the original type to 1000 volts in some forms of the newer. The instrument is illustrated in fig. 100. It has but two terminals, T T, of which, in a simple insulation or leakage test, one is connected to the conductor in the cable under test, while the other is connected to earth. When the insulation between two conductors is being measured, one conductor is

joined to each of the terminals, while the remote ends of both conductors are disconnected. On the front end of the apparatus, as shown in the figure, is a crank handle H, which is attached to a large-toothed wheel as indicated in fig. 102. The wheel gears into a much smaller wheel or pinion, which is mounted on the spindle carrying the armature of the generator. On the top of the apparatus is seen the scale plate P, fig. 100, over which the indicating needle travels. When the instrument is not in use a hinged cover, C, is dropped over the dial or scale plate, and a strap handle, S, which is permanently attached to the instrument at one

FIG. 101



end, is secured at the other end by the link at S, being inserted in the spring clip K. The instrument is thus quite self-contained and is very portable. Facilities are of course provided for bringing the crank handle H into a recess in the wooden case.

The principle involved in the construction of the Megger is illustrated in fig. 101. D is the armature of the generator or dynamo, which is made by means of the handle H (fig. 100) to rotate between the pole pieces *n s*, attached to the permanent magnets S N and N S. At the other ends of these magnets are two more pole pieces, *s n*, and fixed between these pole pieces is a soft iron cylinder B, with a wide longitudinal cleft on one side. A coil

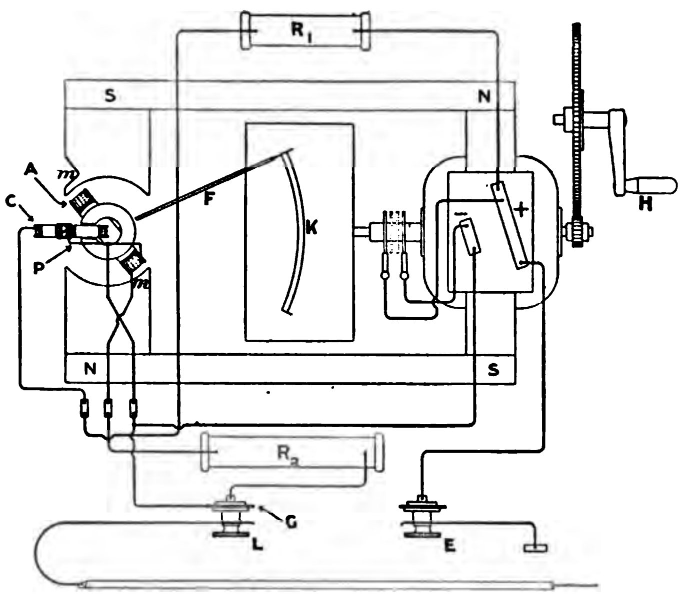
of fine wire A, called the current coil, envelops this cylinder and can rotate freely on its axis. A second coil, or, more correctly speaking, a double coil C, called the pressure coil, is movable about the same axis as the coil A. One half of this double coil can thread itself over the iron cylinder B, and the other half over a peculiarly shaped corner or horn of the soft iron pole piece *s*. Attached to the spindle which carries the movable coils is a pointer F, which travels over the scale plate K. This spindle is fitted at each end with a large and very strong pivot which works in a sapphire bearing, but, notwithstanding the size of these bearings, the movement is perfectly free from friction. R_1 and R_2 are resistance coils, and L and E represent the terminals which are fitted outside the box as shown in fig. 100. The positive (+) and negative (—) brushes rest upon the commutator of the armature, and it will be seen that, supposing there to be an external circuit between the terminals L and E, there are two paths for the current generated in the armature D. One path is from the positive brush direct to E, and from the negative brush through the coil A and the resistance coil R_2 to the terminal L. The other path is from the positive brush through the resistance coil R_1 to the double coil C, and thence to the negative brush of the generator. The latter path is unbroken and invariable in resistance, so that with a given E.M.F. the current is constant, and the field developed by it in the double coil C is also constant. On the other hand, the current which the E.M.F. can maintain in the coil A and the resistance coil R_2 is dependent upon the resistance in the external circuit between the terminals L and E. If no conductors are connected to either terminal then the resistance between those terminals is 'infinite'—that is to say, there is no path whatever for any current (assuming that there is no leakage across the instrument itself from terminal to terminal), and in such circumstances no current will flow through the coil A. If the terminals L and E are joined directly together by means of a short piece of wire of inappreciable resistance, the maximum current will flow and will traverse the coil A. The resistance R_2 is, however, always in circuit and is sufficiently high to prevent a dangerously heavy current passing through A. As the apparatus is designed for the measurement of insulation, the resistance

between L and E, even when the latter is directly connected to earth, should always be considerable, and as a matter of fact the lowest resistance which these instruments are ordinarily made to measure is 1000ω. It will probably have been learned from Chapter IV. (but it will be made clearer in Chapter VII.) that the lines of force between the pole pieces pass more or less directly from one to the other, but most of them will converge upon and pass through the iron cylinder B. Assuming for the moment that no wires are connected to L or E, then on rotating the armature and generating a current, fields of force will be developed in the double coil C, and as a consequence those coils will thread themselves over the cylinder B and the corner piece or horn of *s*. If, however, a circuit even of very high resistance—say, several megohms—be connected to L and E, a current will flow through the coil A, and the lines of force due to that current will be at right angles with the lines of force due to *s n*. The pole pieces are immovable, and consequently the effort of the two sets of lines of force to coincide in direction will result in the coil A rotating through a greater or less angle, the extent of the rotation being dependent upon the strength of the current—that is to say, upon the number of lines of force generated. Of course, if we assume, as we may do, that there is no appreciable resistance to the rotation of the coil A, due to friction and such like causes, the feeblest current should suffice to bring the coil into a position at a right angle with the lines of force due to *s n*, and in order to enable the apparatus to be used as a measuring instrument some restraining device must be introduced. This is the function of the double coil C, which as soon as the current passes through it strives to thread itself as already indicated, and it is against this effort that the current in A has to operate. As this current increases, the coil C is unthreaded, and the coil A rotated towards the 'horns' *m m* (the position shown in fig. 102). Obviously the direction of the current must be such that the coils are made to rotate in a left-handed direction. Otherwise no movement from the position shown in fig. 101 would be possible. It will also be seen that if the current generated should vary, as it would do by varying the speed of rotation of the armature, the variation will also be proportionally varied through A and C, and as a consequence the

position of the needle will in the case of a circuit without electrostatic capacity be unaffected.

The field due to the magnets being permanent, there will always be lines of force passing through the coils A and C, but in the absence of a current through either of these coils there arc no lines of force set up by them, and consequently there is no 'torque' or pull upon either coil. It follows that when the

FIG. 102



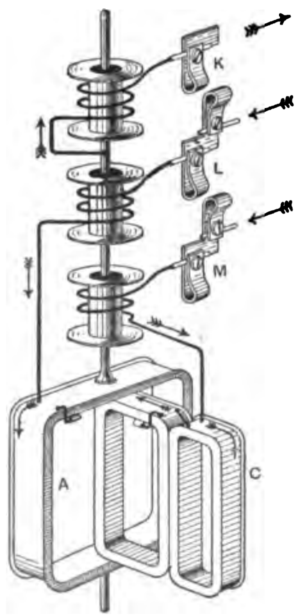
generator handle is at rest, the indicating needle is quite free and will rest indifferently in any part of the scale.

Fig. 102, to which reference has already been made, is a diagram showing the connections between the various parts of the megger, and should be compared by the student with fig. 101. Fig. 103 shows the connections of the moving coil system in all types of megger, of which there are several. K L M are three small terminal plates to which are connected flexible but

springless metal spirals. M is therefore connected to the double coil C, L to the pressure coil A, and K to the insulated spindle to which the other ends of the coils are connected. The corresponding connections in fig. 102 can doubtless be traced by the student.

For the purpose of testing the insulation of instruments and lines which have a very low capacity, variable-pressure meggers, such as we have described above, may be used with advantage. Low-range instruments of this type are made to measure, up to 10, 20, 100, or 200 megohms, the generators yielding an E.M.F. which ranges from 100 to 1000 volts with 100 revolutions of the handle per minute. A high-range instrument of the variable pressure type is made to yield an electro-motive force of 1000 volts and to measure up 2000 megohms. For reasons which will be learned on studying Chapter VIII. the E.M.F. varies with the speed of rotation, so that in order to obtain the standard voltage of any particular instrument it is necessary to revolve the armature at the specified speed. It is easily possible, however, to exceed that speed and to obtain a corresponding higher voltage. There is no serious objection to this when the material which is under test is not liable to break down in its insulating properties. In cases, however, where such risks are involved, and particularly in other cases where the cable under test has an appreciable electrostatic capacity, some device must be adopted for limiting the speed of rotation. The device adopted is to interpose between the driving wheel and the armature of the generator a centrifugal friction clutch, which, when the speed of the handle exceeds 100 revolutions, slips, and

FIG. 103

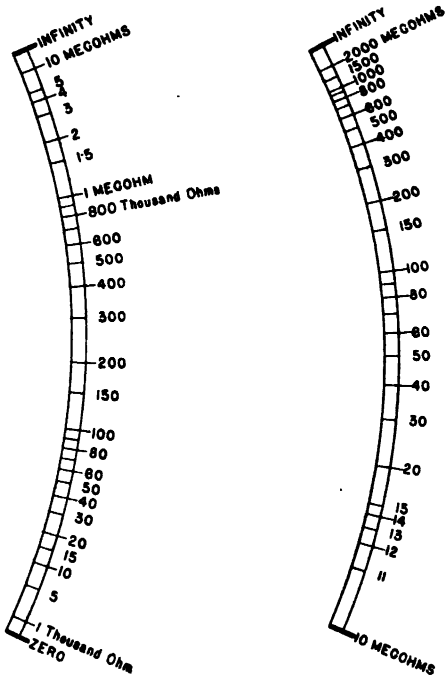


thereby maintains a constant speed in the armature, and therefore also a constant voltage; whence instruments of this type are called constant-pressure instruments. The student will, perhaps, understand that when a circuit has considerable electrostatic capacity, and the voltage is increased, the greater part of the increase will rush into the cable in order to charge it up to the increased voltage, and consequently this additional current will pass through the coil A (fig. 101), and scarcely any through the coil C, whence there will be a sudden deflection of the indicator, although, as a matter of fact, there has been no corresponding diminution in the resistance of the insulating sheathing of the cable. The converse case should also be considered—that is to say, the disturbance of the charge in the cable when the voltage is lowered by a reduction in speed; in such cases there would be a rush of current out of the cable, which would indicate an apparent increase in its insulation. It is therefore necessary to maintain the maximum E.M.F. during a test, and this can only be done by keeping up the speed of rotation. It is specified by the makers that a constant-pressure megger should be used when the electrostatic capacity of the circuit under test exceeds one microfarad. Now a mile of submarine telegraph cable has a capacity of about one-third of a microfarad, and as the surface of the conductor in a lighting or power circuit is usually many times greater than in a telegraph circuit, and as the thickness of the insulating material is very often thinner, it follows that the capacity of a mile of such cable will be correspondingly higher. An ordinary house-installation may easily exceed the stipulated limit. In cases where there is considerable electrostatic capacity it is usually found that with a constant electromotive force the cable will have been charged up and a steady reading obtained after the current has been flowing for a period of one minute. The testing ranges of the constant-pressure meggers and the voltage ranges of the generators are much the same as in the case of the variable-pressure meggers. Typical scales for low and high range instruments are given in fig. 104, and in both cases it will be seen that the scale is more open in the early than in the later parts, although the difference is not particularly great; for example, if in the low range scale we start at 10,000" there is about

the same extent of scale-space between $20{,}000^{\omega}$ and $40{,}000^{\omega}$ as there is between $10{,}000^{\omega}$ and $20{,}000^{\omega}$. Similarly the space between $200{,}000^{\omega}$ and $400{,}000^{\omega}$ is about the same as between $400{,}000^{\omega}$ and $800{,}000^{\omega}$. A similar state of affairs will be manifested on studying the high range scale.

Although the instrument has only recently been produced it is very extensively used, and its negative advantages have been not inaptly proclaimed in the following terms:— There are no switches, no plugs, no adjustments, no key to be tapped, no galvanometer to watch, no rheostat to adjust. Its positive advantages may be summed up by saying that it is portable, direct reading, simple, and reliable, free from disturbance by stray magnetic fields, measures under high E.M.F. and is very prompt in its indications.

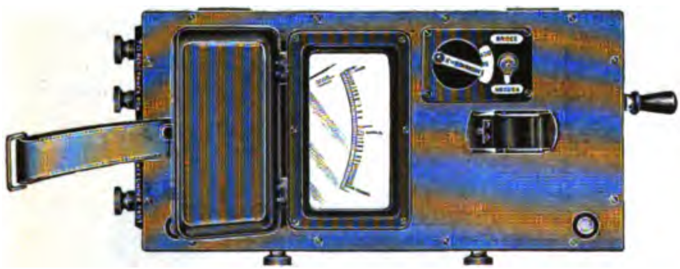
FIG. 104



A very ingenious modification of the instrument is known as the Bridge-megger, and, as its name implies, it may be used either as a Wheatstone bridge, for measuring comparatively low resistances, or as an ordinary megger with a range up to 40 megohms. A plan of the top of the containing-box is shown in fig. 105, and it will be seen that at the right-hand end there are two switches; one

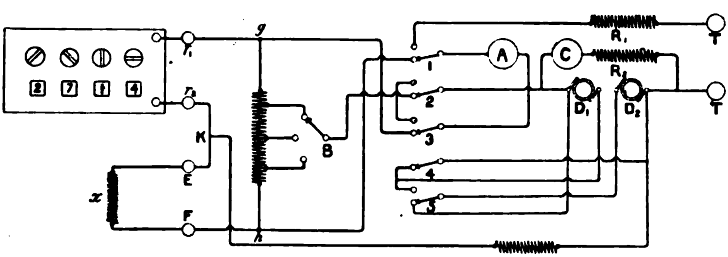
of these is a two-way switch, which in one position joins up the instrument as a megger, and in the other as a Wheatstone bridge. The second switch is a ratio switch, which is only required when the two-way switch is turned to 'Bridge,' and which is used to vary the two ratio arms of the bridge after the

FIG. 105



manner of the slider on the slide wire bridge described earlier in this chapter (see fig. 92). There are six terminals, the two in the front, as shown in the figure, being used when the instrument is required to work as a megger, and the four at the end when it is required for bridge measurements. Apart from the switches, the

FIG. 106



consequent facilities for altering the internal connections, and the addition of the ratio resistances, the construction of the bridge megger is substantially the same as the megger.

Fig. 106 shows the complete internal connections of the instrument and the method by which the change from megger to bridge measurements is effected. The two-way or change-over

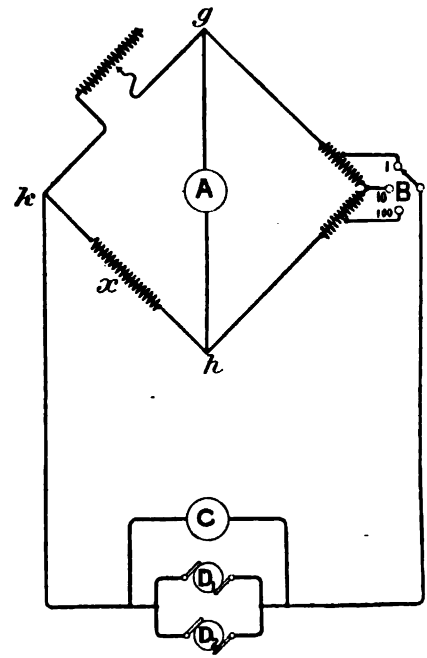
switch is supposed to have been set to 'bridge.' T T represent the front terminals in fig. 105, and as the instrument is joined up for bridge working they are left disconnected externally; r_1 r_2 are terminals which are joined to a separate box of resistance coils (fig. 107), and which perform the function of the adjustable resistance D E in fig. 94. E F (fig. 106) are the terminals to which the unknown resistance x is connected. B is the ratio switch which can be placed in one or other of three positions. The resistances controlled by this switch can, by transferring the arm to one or other of the contact studs, be so varied that the reading in the

FIG. 107

resistance-box when a balance is obtained shall be equal to the resistance of the circuit under measurement, or shall be ten or one hundred times that resistance. The change-over switch is more complicated, for when the switch is turned there are five switch bars—1, 2, etc.—to be moved simultaneously. These switch bars perform a variety of functions. The generator is of the constant-pressure type previously referred to, and is provided with two windings which can be joined in series for megger working or in parallel for bridge working. When in series the E.M.F. is 500 volts, and when in parallel the E.M.F. is only 250 volts; but the internal resistance is in the latter case reduced to one-fourth, and

a much stronger current can be developed. The two windings are represented in fig. 106 by D_1 D_2. If we suppose the right-hand side of each winding to be the positive pole, the positive brush of D_1 is joined by switch No. 4 to the positive brush of D_2, while the negative brush of D_1 is joined by switch bar No. 5 to the negative brush of D_2. The current coil A and the pressure coil C are here shown separately, but they occupy actually the same relative positions as in figs. 101 and 102. The coil C and its resistance R_2 are permanently joined across the terminals of the generator, which is practically identical with the arrangement shown in fig. 101. There is a wire permanently connected to the negative brush of D_1 and to switch bar 2, whereby the negative pole of the generator is joined to the ratio switch B, which corresponds with the point B in fig. 94. Similarly the points g and h and the terminals r_1 and F correspond to the terminals A and C in fig. 94. The positive pole of the generator is joined through a protective resistance coil to the point K, and thence direct to the terminals r_2 and E, which correspond to the terminal E in fig. 94. The current coil A is joined on the one side by means of switch bar 3 to the point g, and on the other side by means of switch bar 1 to the point h. This coil therefore performs the function of the galvanometer in the Wheatstone bridge apparatus. The

FIG. 108

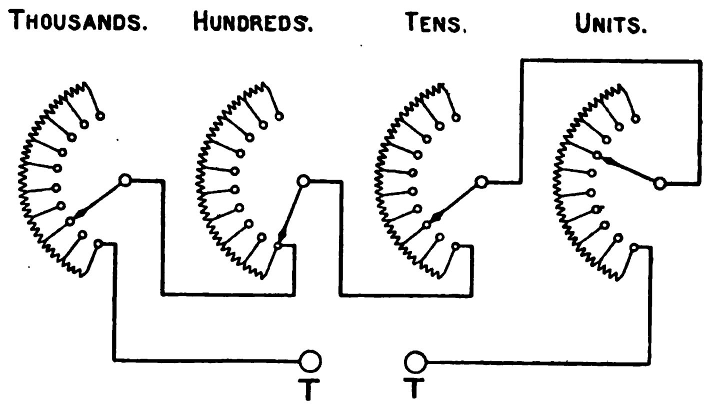


function of the pressure coil C is to control the movements of the coil A.

The student will, no doubt, be able to identify the positions for bridge working shown in fig. 106 with the usual diamond formation illustrated in fig. 108, which is similarly lettered.

A further reference may now be made to the resistance box illustrated in fig. 107. This box, which, as we have said, is independent of the box containing the megger apparatus, is provided with a pair of flexible leads for coupling it to the terminals r_1 r_2 of the bridge-megger. The coils are wound with 'Eureka' wire, an alloy which varies in resistance only very

FIG. 109



slightly with variations in temperature, and which is very serviceable for providing definite and fixed resistances. The wire is not double wound, as the applied voltage being constant, self-induction in the coils is immaterial. The internal connections of the box are indicated in fig. 109. There are four sets of uniform coils, units, tens, hundreds, and thousands—that is to say, the first set consists of nine coils each of one ohm resistance, the second of nine coils each of ten ohms resistance, and so on, so that the total resistance amounts to 9999 ohms. Each set of coils is controlled by a separate switch (see fig. 107), and each of the four switches carries a figure dial arranged to show (through a

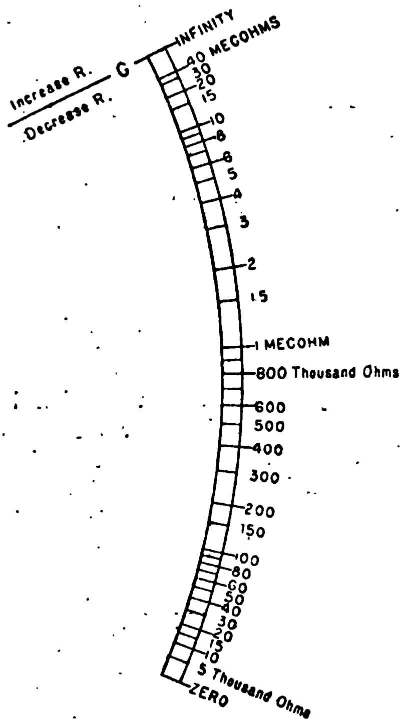
small ' window ' in the top plate) a digit representing the position of the switch. The total resistance inserted by the switches is thus given directly in a row of figures which can be read off with ease, as will be seen by reference to the view of the box given in fig. 106. In this way all risk of error due to miscounting is avoided. In the positions of the switches indicated by the arms in fig. 109, the figures exposed would be 2027 and would mean that the resistance inserted is 2027^{ω}. As we have already stated, the total resistance is 9999 ohms, and as, by the movement of the ratio switch, the resistance to be measured may be either equal to the resistance of the box or one-tenth or one-hundredth of that amount, it follows that the range of the instrument is from 0·01 ohm to 9999 ohms. If, for example, the ratio switch is so placed that the resistance in circuit in the box is one hundred times the resistance of the circuit under measurement, and if the former resistance is 13 ohms, the latter is 0·13 ohm.

Resistances of $10{,}000^{\omega}$ or more may be tested on the megger principle by turning the change-over switch and joining the circuit to be measured to terminals T T (fig. 106), or the resistance-box, and the unknown resistance may be reversed in position by joining the box to terminals E F, and the unknown resistance to terminals r_1 r_2, and continuing to use the apparatus on the bridge principle. The ratio switch can still be operated as before—that is to say, the resistance in the box between the terminals E F will, according to the position of the ratio switch, be either equal to the unknown resistance or one-tenth or one-hundredth of that resistance. If the total resistance in the box is a maximum, or 9999^{ω} when a balance is obtained, and if the switch is so placed that the larger multiple is used, the resistance under measurement is $999{,}900^{\omega}$. It follows that the range of the bridge as now joined up is from 1^{ω} to a maximum of 999,900 , although for resistances under $10{,}000^{\omega}$ it is preferable to join up the apparatus as indicated in fig. 106.

In using the bridge the current is, of course, applied by rotating the handle of the generator, and a balance is obtained when the resistance in the box is so adjusted that the points *g h* are brought to a common potential. Obviously under such circumstances, no current will flow through the current (or galvanometer)

coil A, and the pressure coil C will alone be effective and will hold the needle against the zero. A copy of the scale of the bridge-megger is given in fig. 110, and for bridge purposes the zero is at G. The indicating needle can swing to either side of this point when the resistances are out of balance, and, as indicated in the figure, the resistance must be increased or decreased, as the case may be, in order to obtain a balance and bring the needle to its proper position. It will doubtless be remembered that, as the reading of an ordinary bridge galvanometer is taken when the needle is undeflected, no scale is required, all that is really necessary being a zero point to indicate that no current is flowing round the galvanometer coil. Hence no scale properly so-called is needed when the bridge-megger is used as a bridge. It is advisable, when commencing a bridge test, to cut out all the coils in the resistance box by setting the four handles or switches at their respective zeros, and then to turn the generator handle slowly. The needle will, if the apparatus is joined up as in fig. 106, immediately take up a position off or beyond the scale—that is to say, on the side marked 'increase R.' The generator handle being still slowly rotated (so as to generate a comparatively feeble E.M.F. and avoid any risk of injury by over-heating), the resistance switches should be

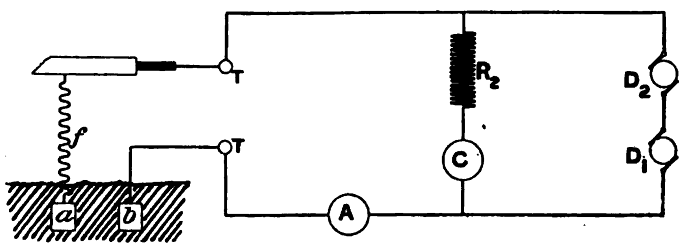
FIG. 110



turned by hand, beginning with the thousands. If 1000° should prove too high—that is to say, if the needle is deflected to the opposite side of the scale, the resistance switch should be reset at its zero, and the hundreds switch rotated. Let us suppose that with 500 in circuit the needle is retained above or on the blank side of G, while with 600° in circuit it is transferred to the lower side. In such circumstances the hundreds switch should be reset at 5 (that is 500°), and the tens switch should then be turned until the needle passes once more to the lower side of G. Let this happen when the tens switch indicates 7 (that is 70°). We then know that the required resistance is somewhere between 560° and 570°. All that is then necessary is to reset the tens switch at 6 and move the units switch until the needle comes to rest at G. If this happens when the units switch indicates 8 (or 8°), the required resistance is 568°, and if the ratio switch happens to be turned so that the resistance box is ten times the resistance under measurement, that resistance is now known to be 56·8°. It should be remembered that as we approach the correct resistance the potential difference between *g* and *h* (fig. 106) with a given E.M.F. falls so that as the final tests are approached the speed of rotation of the generator handle should be increased, until when it is thought that a balance has been almost obtained, the full speed of 100 revolutions per minute should be applied. It will also be remembered that in speaking of insulation tests with the high-range megger, stress was laid upon the necessity for running the generator at its maximum speed of 100 revolutions by increasing the rotation of the handle until the friction clutch is felt to be slipping. The object of this, it will be remembered, was to obtain a constant E.M.F., and thereby to avoid oscillation of the needle as a consequence of a variable charge flowing in or out of the cable. Similarly, if the circuit under test when the bridge side of the bridge-megger is in use happens to have any appreciable self-induction, as would be the case when, say, a dynamo field-magnet or any other electro-magnet is under test, it is essential that the maximum speed of the generator, 100 revolutions, and the maximum and constant E.M.F. of 250 volts, should be obtained, in order that any oscillation of the needle consequent upon induced currents should be avoided.

When it is desired to test resistances of 10,000$^{\omega}$ or more and the positions of the resistance box and the unknown resistance x are the reverse to that shown in fig. 106, it will, of course, be necessary to reverse the directions given on the scale, fig. 110—that is to say, the needle will start *below* G, and the resistance in the box should be increased until the needle travels to the upper or plain side of the scale, and so on. In other words, 'increase R' and 'decrease R' should be read inversely. The scale shown in fig. 110 is required when the apparatus is used as a megger, and starts from the end remote from G—that is to say, when there is no resistance in the external circuit, or when the terminals are short-circuited, the indicating needle stands at 'zero,' and passes over the scale as the resistance rises, so that when the

FIG. 111



resistance is considerably over 40 megohms it approaches the 'infinity' mark, which is identical with G. In both cases, whether the instrument is joined up as a bridge or as a megger, the deflection of the needle to G or 'infinity' indicates that there is no perceptible current passing through the coil A.

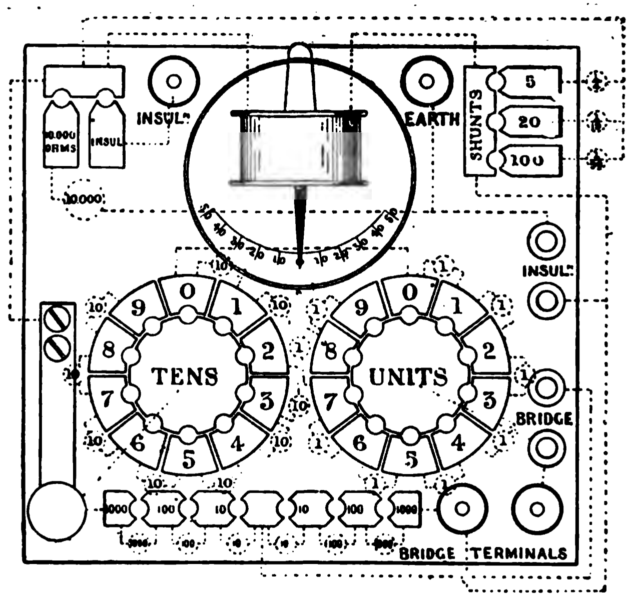
We come now to the connections for megger working, and fig. 111 shows in a very simple fashion the skeleton arrangement. Referring to fig. 106 we will suppose that the change-over switch is turned to 'megger.' In these circumstances the five switch bars will be raised and make contact with the upper sets of switch blocks shown in the figure. The ratio switch may be disregarded, as there will be nothing connected to terminals r_1 r_2 E F. The ratio resistances between g and h are also disconnected at their respective switch blocks. The lettering of the two diagrams

is the same for the same parts. It will be seen (fig. 111) that the two dynamo windings D_1 and D_2 are joined in series to give the maximum E.M.F. of 500 volts; and that one pole of the generator is connected by means of one of the terminals T direct to the conductor of the cable. The other pole of the generator is joined through the current coil A and the second terminal, T, direct to earth. The pressure coil C and its protective resistance are joined in the same fashion as in the ordinary megger—that is, as a shunt across the main circuit. The distant end of the cable is assumed to be disconnected, and *f* represents the high-resistance leakage from the conductor through the insulating material to earth. This leakage may be at one point (which would therefore be regarded as a fault), or it may be generally distributed, and if considerable in amount it would point to inferiority in the insulating properties of the sheathing.

Another useful set of apparatus is that known as the Silvertown portable testing set, which is contained in two small wooden boxes, one holding the batteries which are employed for the test, and the other the galvanometer, resistance coils, key, and commutator. The apparatus is designed for facilitating tests of the resistance of the conductor itself, as well as of the insulating materials. Two separate batteries are employed—one of them consists of three low-resistance Leclanché cells, and is used for testing the conductor resistance; the other battery consists of thirty-six small Leclanché cells, which are divided into three sections, so that an electro-motive force of about 5, 25 or 60 volts can be employed as occasion requires. The batteries are connected with the other apparatus by means of wires terminating in brass plugs, which are provided with ebonite handles, and which fit into circular plug-holes on the top of the box containing the measuring apparatus. This box, of which a plan is given in fig. 112, contains a sensitive horizontal galvanometer, the coil of which consists of many turns of fine wire. The needle is delicately mounted on a pivot, and carries a long but light aluminium pointer, which protrudes beyond the coil and travels over a scale. The pivot is carried by a small slide, by means of which the needle can be withdrawn from the instrument for examination or repair. The needle is so magnetised that when the pointer is

swinging freely and comes to rest in the zero position, the north-seeking pole of the needle is then pointing to the left-hand side of the box. Mounted in a recess on this side is a controlling magnet, the upper end of which, when in the vertical position, is nearer to the needle than the lower end. From what was said when describing the tangent galvanometer, it will be gathered that when the controlling magnet is placed with its north-seeking

FIG. 112



pole upwards, it is acting in antagonism to the earth's field, and by thus reducing the value of the controlling force the sensitiveness of the instrument is increased and a feebler current is required to produce any given deflection. When the magnet is reversed the controlling force is augmented—that is to say, the lines of force due to the magnet act in conjunction with those due to earth, and the sensitiveness of the instrument is reduced. The difference between the maximum and minimum values as affected

by the positions of the controlling magnet is about 40 per cent. Insulation-resistance tests are usually effected with the galvanometer in its most sensitive condition, while the resistance of conductors is usually tested with the controlling magnet in the position for least sensitiveness—that is, with its south-seeking pole upwards. The controlling magnet is also of service in adjusting the needle to zero. In preparing to test, the box should be placed on a fairly level surface, with the left side towards the north, and the controlling magnet in a vertical position. The needle will then swing at or about its zero position, to which it can be brought exactly by a slight inclination of the controlling magnet to one side or the other. The dotted lines in the illustration (fig. 112) indicate the whole of the permanent electrical connections made inside the box.

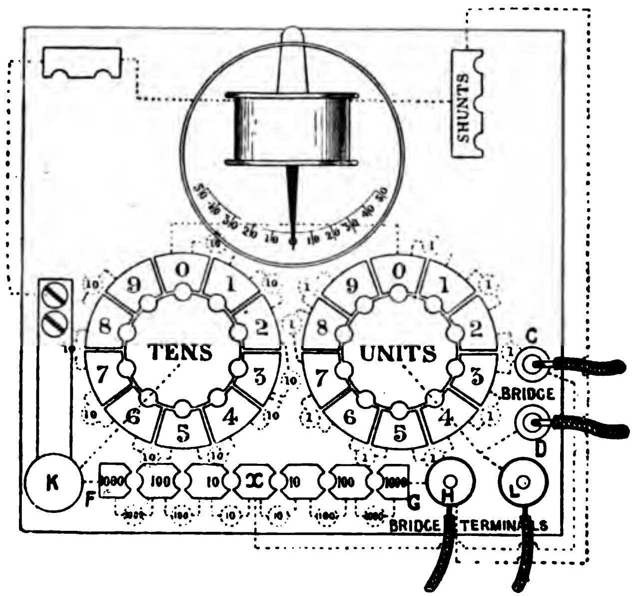
In order to measure a low resistance, such as that of an electric-light conductor, the connections are such as to convert the apparatus into a Wheatstone bridge, and to facilitate the tracing of these connections a separate diagram (fig. 113) is furnished, embracing only those parts of the apparatus required for this particular test. The poles of the battery are joined to the terminals C and D respectively. From C the current travels to the block *x*, where it divides between the two arms of the bridge, each of which contains three coils of 10^{ω}, 100^{ω}, and 1000^{ω}, as in the Post Office bridge (fig. 94). It will be remembered that in every test one of the coils should be used in each of these arms. From the block F the current passes to another bridge-arm, consisting of a couple of rheostats, one comprising 10 coils each of 1^{ω} resistance, and the other 10 coils each of 10^{ω} resistance, so that the maximum resistance of this arm is 110^{ω}. The diagrams figs. 112 and 113 show only 9 coils, but there is a tenth coil in each case so arranged that when the plug is removed from either rheostat, the circuit is not disconnected, as would be the case were all the coils joined up in the manner illustrated. The connections for these rheostats are similar to those in the form of bridge illustrated in fig. 99. It will be seen that the centre plate of the 'tens' rheostat is connected to the block F, and that the centre plate of the 'units' rheostat is connected to the terminal D (to which we have already connected one pole of the battery). The two zero

or O blocks of the rheostats are connected together, and the coils are joined between the other blocks as shown in the figure.

To complete the other side of the bridge, block G is connected to the terminal H, and between this and terminal L is joined the conductor whose resistance has to be ascertained.

Between the blocks F and G the galvanometer must be connected, the path for which through the key, K, is shown by the

FIG. 113

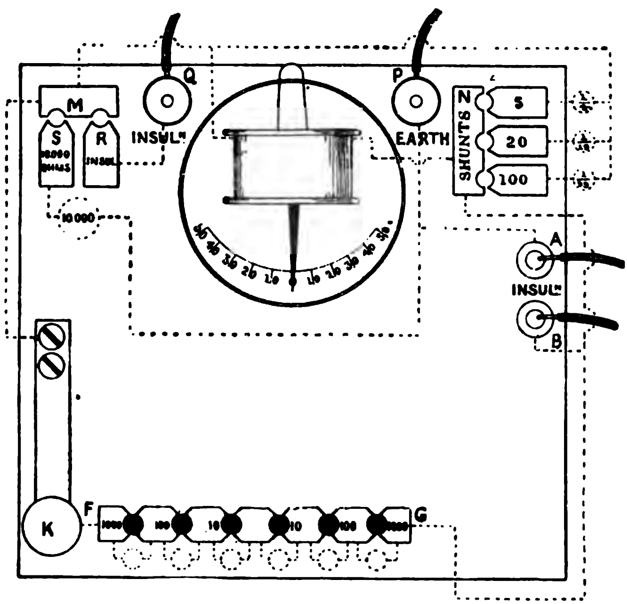


dotted lines. Theoretically the range of the bridge extends to 11,000ω, but practically it is more restricted than this, the working range of the instrument being from 1ω to 1000ω. Outside these limits an increase of battery power is necessary in order to obtain satisfactory results.

Fig. 114 shows the positions of the apparatus employed and the connections involved for testing insulation resistance. One pole of the battery is joined to terminal A, which is connected direct

to earth by way of terminal P. The other pole of the battery is joined to terminal B, which is connected to the 'shunt' block N, from which the current passes direct to the galvanometer and thence to another block, M. A plug is employed to continue the path to the block S, and thence through a resistance of 10,000ω, to the pole of the battery connected to terminal A. The galvanometer, however, being somewhat sensitive, gets

FIG. 114



too much current when the resistance in circuit with the full battery is only 10,000ω, and it will be observed that between the shunt block N and the block M there are three shunt paths having reducing powers of 5, 20, and 100 respectively. If we suppose the highest shunt to be employed, then the galvanometer reading should be multiplied by 100, or, what amounts to the same thing, if the galvanometer with the one-hundredth shunt gives with the 10,000ω coil in circuit a deflection of, say, 25 divisions, then

the same deflection would be obtained were the unshunted galvanometer placed in circuit with a resistance of 10,000 × 100 = 1,000,000ω. But if the battery can produce a deflection of 25 divisions through 1 megohm, it will give one division through 25 megohms, and this latter resistance may be called the 'constant' of the instrument under these particular conditions. This constant we consider a better and simpler one to employ than that usually adopted, although of course the ultimate results are the same. We repeat, then, that the constant which we adopt is the value of that resistance through which the battery employed can produce a deflection of one division on the unshunted galvanometer. Having determined the constant, we are now in a position to make an insulation test. Let the plug be removed from the hole between M and S, and now placed in the hole between M and R. The current will then pass to terminal Q and thence into the conductor of the cable under test, one end of the conductor being joined to Q, the distant end being of course carefully insulated. Should the unshunted galvanometer now give a deflection of 25 divisions, the resistance of the insulating material is clearly 1 megohm. One or other of the shunt coils can, if necessary, be used in this test as well as in the preliminary test for the constant, and the reading of the galvanometer should then be multiplied accordingly in order to obtain the theoretical deflection which the unshunted galvanometer would give. Suppose, for example, that the insulation resistance is so low that when the twentieth shunt is employed by inserting the plug, the reading obtained is $12\frac{1}{2}$ divisions, then the deflection on the unshunted galvanometer would be $12\frac{1}{2} \times 20 = 250$ divisions. But one division corresponds to 25 megohms, therefore 250 divisions would indicate a resistance of $\frac{25,000,000}{250} = 100,000$ ohms. In fact, to obtain the value of any resistance it is sufficient to divide the 'constant' by the deflection which would be obtained through that resistance on the unshunted galvanometer.

The key, K, can, with the holes in the blocks from F to G plugged up, be employed as a means for short-circuiting the galvanometer. This is frequently a great convenience, as its use facilitates the reading of the instrument by checking the oscilla-ns of the needle.

CHAPTER VI

MEASUREMENT OF ELECTRO-MOTIVE FORCE.

IN all classes of electrical work it is important to be able to accurately measure potential difference, or electro-motive force, and no better introduction to this branch of the subject can be obtained than that furnished by the study of the methods by which the electro-motive force of primary batteries can be compared. By Ohm's law we know that $E = C R$, where R is the total resistance of any circuit measured in ohms, C the current in amperes flowing through it, and E the electro-motive force in volts which maintains that current. So that, whenever the resistance and the current strength are known, the E.M.F. can be ascertained by multiplying these two quantities together. For instance, if a battery having a resistance of 15 ohms is joined up to send a current through a galvanometer of 320 ohms resistance, with a rheostat having 960 ohms unplugged, also in circuit, and if the resulting current is found to be 8 milliamperes, then the electro-motive force of that battery is $C \times R$ or $\cdot008 \times 1295 = 10{\cdot}36$ volts. The measurement of current strength presents but little difficulty, but it is not often that the total resistance in the circuit is accurately known without measurement, and thus two tests at least are rendered necessary in order to ascertain the E.M.F. by this method. A more direct method is to take some good constant cell or battery whose E.M.F. is known exactly, and compare the unknown electro-motive forces with that of this 'Standard' cell or battery. The accuracy of the results depends, of course, upon the accuracy of the value which is given to the E.M.F. of this standard, and upon its constancy.

A very good cell for a standard is that devised by Latimer Clark, and described in Chapter III. If carefully used it will

remain constant for years; but, as it polarises quickly, it should not be allowed to send so strong a current as even one milliampere, and, if possible, should only be used in those tests, to be described presently, in which the batteries are tested when they are not sending any current at all, but simply maintaining a potential difference. A rather serious drawback to this cell is, that its E.M.F. varies appreciably with a change of temperature, falling as the temperature rises; and although, the temperature being known, the variation of E.M.F. can be allowed for, such calculations are inconvenient and take time. Its E.M.F. at 15° Centigrade is 1·434 volt. The student will perhaps remember that it was pointed out that a new cell—the Weston Cadmium—is rapidly displacing the Clark cell for standard purposes, mainly because its E.M.F. does not vary materially with changes of temperature, and secondly because it is not seriously injured by the passage of a heavy current.

The Daniell cell when in good condition does not polarise, even when developing a strong current, and it has the further advantage that a considerable variation of temperature makes little or no difference in its E.M.F. It is, therefore, a good standard for use in the workshop, and any form of Daniell cell in first-rate order may be employed, especially when the tests are independent of the battery resistance. But it must be remembered that the plates should be bright and clean, the supply of crystals in the copper cell plentiful, and the solution in the zinc cell half saturated. The E.M.F. is then 1·079 volt.

Since the current which a battery can develop is proportional to its E.M.F., it is evident that the E.M.F. of two batteries can be compared by observing the currents which they send through circuits offering *equal* resistances. The Daniell cell should be used as the standard in this case, and if it give on a tangent galvanometer 25 divisions deflection through a total resistance of, say, 1000$^{\omega}$, while another cell or battery gives 62·5 divisions through the same resistance, then

$$25 : 62{\cdot}5 :: \text{E} : x,$$

where E is the E.M.F. of the standard cell, and x that of the battery under measurement.

Therefore $$x = \frac{62 \cdot 5 \times 1 \cdot 079}{25} = 2 \cdot 7 \text{ volts nearly.}$$

One objection to this method, when the external resistance is low, is, that it is necessary to know the resistance of the batteries, in order that the total resistance may be made the same in both cases; but if the resistance of the external circuit is comparatively high, as in the case just considered, then the resistance of the batteries may be ignored.

In this simple method the resistance is kept constant while the current varies. The different currents are then measured and the relative E.M.F. deduced therefrom directly, as the E.M.F. varies directly as the current produced.

But it is also possible to compare electro-motive forces by varying the resistance and keeping the current constant, in which case the electro-motive force is proportional to the resistance; for, the higher the E.M.F., the greater is the resistance through which it can send a given current. One great advantage in connection with this method is, that any kind of galvanometer which may be available can be employed, because the same deflection is produced in every case. In order to compare the E.M.F. of any battery x, with the standard cell E, we should in this method join up the standard cell in circuit with a rheostat and galvanometer, varying the resistance so as to obtain a convenient deflection of, say, 45°, and noting carefully the total resistance, R_1, in circuit. The battery to be tested should next be joined up, and the resistance altered, say, to R_2, so as to reproduce the deflection of 45°.

Then $$x : E :: R_2 : R_1, \text{ or } x = \frac{E\,R_2}{R_1}.$$

In this test, also, the resistances of the standard cell, the battery, and the galvanometer must be known and taken into account, unless the resistance in the rheostat is comparatively high, when these other resistances may be ignored.

But by a simple extension of this method, it is possible to obtain an accurate result without knowing any one of these three resistances. The process consists in first joining up the standard cell, E, in the same manner as in the previous test, and then

adjusting the rheostat until a deflection of, say, 45° is obtained. The resistance should then be increased until the deflection falls to, say, 35°, noting carefully the exact number of ohms, P, by which the resistance is increased, in order to bring about the reduction in the deflection. The battery, whose electro-motive force, x, it is desired to measure, must now be substituted for the standard cell, and the resistance again adjusted until the deflection of 45° is reproduced. This resistance should then be increased by, say, Q ohms until the deflection is once more 35°. Then as shown below,

$$x : \mathrm{E} :: \mathrm{Q} : \mathrm{P}, \text{ or } x = \mathrm{E}\frac{\mathrm{Q}}{\mathrm{P}} \text{ volts.}$$

To take an example. If with the Daniell cell as a standard the insertion of 720 ohms reduces the deflection 10°—that is to say, from 45° to 35°—and when the battery whose E.M.F. is to be measured is substituted it is found necessary to add 2300 ohms to reduce the deflection through the same 10°, then

$$x = 1\cdot079 \times \frac{2300}{720} = 3\cdot446 \text{ volts.}$$

This is a very good method, and it is interesting and instructive to observe how the battery and galvanometer resistances are eliminated. This may be shown by Ohm's law as follows:

Let G be the resistance of the galvanometer, r_1 the internal resistance of the standard cell, and R_1 the resistance in the rheostat when the needle is deflected through 45° by the current whose strength is indicated by C_1, then

$$\mathrm{C}_1 = \frac{\mathrm{E}}{\mathrm{R}_1 + r_1 + \mathrm{G}}.$$

Also let r_2 be the resistance of the battery whose E.M.F. is to be deduced, and R_2 the resistance in the rheostat necessary to reproduce the deflection of 45°, or when the current strength can again be indicated by C_1, then

$$\mathrm{C}_1 = \frac{x}{\mathrm{R}_2 + r_2 + \mathrm{G}},$$

therefore $$\frac{E}{R_1 + r_1 + G} = \frac{x}{R_2 + r_2 + G}$$

or $$E(R_2 + r_2 + G) = x(R_1 + r_1 + G) \quad . \quad . \quad (1).$$

When the resistances R_1 and R_2 are increased by P and Q respectively to obtain the deflection of 35° which will correspond to a current strength which can be called C_2, then

$$C_2 = \frac{E}{R_1 + r_1 + G + P} = \frac{x}{R_2 + r_2 + G + Q},$$

therefore $E(R_2 + r_2 + G) + E\,Q = x(R_1 + r_1 + G) + x\,P \quad . \quad (2).$

Subtracting equation (1) from (2) we get

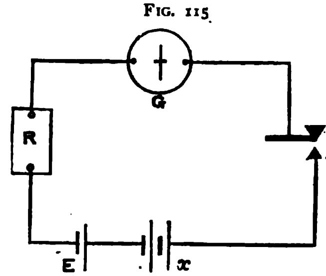
$$E\,Q = x\,P,$$

therefore $$x = E\,\frac{Q}{P}.$$

To ensure accurate results it is essential that the galvanometer for this test should be sufficiently sensitive to indicate a very slight alteration in the current strength, and, if possible, the resistances P and Q should be as high as or even higher than the total resistance in the circuit prior to their insertion.

There is another good method which is sometimes very convenient because it is not necessary to know or ascertain the actual resistance of any portion of the apparatus, whether it be the galvanometer, the rheostat, or the battery. As in the previous tests, we may denote the E.M.F. of the standard cell by E, and that of the battery to be measured by x. The standard cell E and battery x are joined up in series, so that they assist each other in sending a current through a rheostat or set of resistance coils, R, and a tangent galvanometer, G (fig. 115), and the resistance adjusted until a fairly high deflection, say, sixty-five tangent divisions, is obtained. Then, on reversing the standard cell (supposing it to be of lower

FIG. 115



E.M.F. than x) so that the two E.M.F.'s, x and E, are opposed to each other, the resulting current will manifestly be due to the *difference* between the two E.M.F.'s, and, as the total resistance remains unaltered, the current and the deflection produced by it will be diminished, say, to twenty-five divisions. Then, denoting the first deflection (sixty-five divisions) due to both E.M.F.'s by D, and the second deflection (twenty-five divisions), due to the *difference* between the two E.M.F.'s when opposed, by d,

$$x : \mathrm{E} :: \mathrm{D} + d : \mathrm{D} - d,$$

or

$$x = \mathrm{E}\,\frac{\mathrm{D} + d}{\mathrm{D} - d}$$

Inserting the values as above, we get

$$x = 1{\cdot}079 \times \frac{65 + 25}{65 - 25} = 2{\cdot}428 \text{ volts.}$$

The object of reversing the battery or cell of lower E.M.F. is to obtain both deflections on the same side of the zero point. Were the battery of higher E.M.F. to be reversed, it would cause the second deflection to be obtained on the opposite side of the zero, and if the instrument were not perfectly symmetrical an incorrect result would be obtained. If, when joined up in opposition, no deflection is obtained, then the electro-motive force of the standard cell will be the same as that of the battery under test, or $\mathrm{E} = x$.

The only objection to the method is that in the first case the weaker battery, which is usually the standard cell, has a rather strong current flowing through it which may lower its E.M.F., while, when joined in opposition, the current is passing in the opposite direction and will almost certainly cause a slight increase in its E.M.F. In order to eliminate as much as possible this source of error, it is advisable to introduce a 'key' or contact-maker to open and close the circuit at will, as shown in fig. 115. By the skilful manipulation of this key the needle can be brought to rest immediately without a single oscillation, and the deflection then read before any appreciable alteration of the E.M.F. can take place. As a further precaution, the resistance in circuit should be made fairly

high so as to reduce the strength of the current. By such means the objection becomes almost entirely obviated. To admit of high resistance being placed in the circuit, the 320° coil of the galvanometer should be used unshunted, and the magnet placed rather low down with its north pole pointing northwards, so that it will act in opposition to the earth's magnetism, and by thus weakening the earth's field increase the sensitiveness of the instrument.

That the resistance of the batteries and galvanometer need not be known or ascertained is evident from the fact that they form part of the constant total resistance, which is the same in each case and which need not enter into the calculation. This may be shown algebraically, for if we let R indicate the total resistance in circuit (including batteries and galvanometer), C_1 the current in the first case giving deflection D, and C_2 the weaker current giving deflection d, then

$$C_1 = \frac{x + E}{R}, \text{ or } R = \frac{x + E}{C_1},$$

and

$$C_2 = \frac{x - E}{R}, \text{ or } R = \frac{x - E}{C_2}.$$

Therefore $\frac{x + E}{C_1} = \frac{x - E}{C_2}$, or, since the currents are proportional to the deflections in tangent divisions, $\frac{x + E}{D} = \frac{x - E}{d}$.

Whence

$$Dx - DE = dx + dE$$
$$x(D - d) = E(D + d),$$
$$x = E\frac{D + d}{D - d}.$$

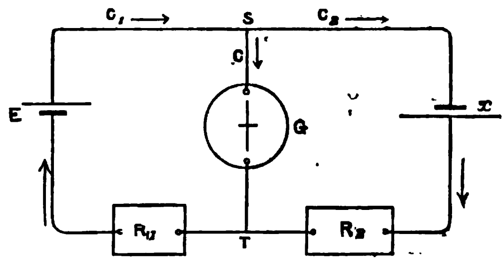
It will doubtless be remembered that, if the poles of a battery are joined by a short piece of thick wire having practically no resistance, the current flowing through the circuit will depend simply upon the E.M.F. of the battery and its internal resistance. Now, the thick-wire coils of the tangent galvanometer which we have described are of very low resistance, and may be used for the measurement of the current which a battery can give under these conditions. Thus, supposing a battery of twenty Daniell cells, having a resistance of 5 ohms per cell, were joined up to send

a current through one of the low resistance coils of the tangent galvanometer, the current flowing would be $\frac{20 \times 1{\cdot}079}{20 \times 5} = 0{\cdot}2158$ of an ampere, and the current from one cell, or 100 similar cells, should be the same, because when the E.M.F. is increased by increasing the number of cells, the internal resistance—that is, the total resistance in circuit—is increased in the same proportion. A galvanometer with a very low resistance coil affords, therefore, a means of rapidly testing the *condition* of a number of similar batteries, for the deflection of the needle will be decreased if either the internal resistance of any cell is above, or the E.M.F. of any cell below, the standard. It is, then, only necessary to ascertain the deflection given by a cell or a battery known to be in good condition, and adopt this as the standard. Then if a battery, say, of ten cells give a current equal to that of the standard cell, it may be fairly concluded that the battery is in good condition, but if a second similar battery give a deflection of seven or eight degrees less, then the conclusion is that there is something wrong with it; its resistance is too high or its E.M.F. too low. The latter may be quickly decided by joining up the faulty battery in opposition with the similar battery known to be good—that is to say, joining their copper or positive poles together and their zinc or negative poles one to each terminal of the galvanometer. If they then give no deflection, we know that their electro-motive forces are equal, and the fault is proved to be one of high resistance. If, on the other hand, a current is produced, there must be a difference in E.M.F., and the fact that the suspected battery is the faulty one would be demonstrated if the direction of deflection were such as to prove that the other is urging a current through it.

But galvanometers with short thick wire coils having but a few convolutions are only affected by very powerful currents, and are, as a rule, only used where it is essential that the introduction of the instrument into any circuit should have no appreciable effect upon the strength of the current flowing through it. When this restriction is not imposed increased accuracy can usually be obtained by employing a more delicate instrument, in which a coil of many turns, and generally of fine wire offering a high resistance, is employed; because, although the current through the galvano-

meter is weakened by the added resistance, the effect is more than balanced by the increased number of times which the current travels round the needle. In fact, the flow of a very feeble current through such an instrument, or the maintenance of a very low difference of potential at its terminals, may suffice to produce a good deflection, while under similar conditions a galvanometer with a thick wire coil would be unaffected. It was observed when considering the Wheatstone bridge method of measuring resistances (Chapter V.), that one great advantage pertaining to it is, that in making the final adjustment only a very weak current or no current at all passes through the galvanometer. It is therefore practicable in such cases to use a very delicate instrument, and, in order to prevent damage being done to the needle or its pivot, or

FIG. 116



to prevent the coils being fused by the passage of a heavy current, the coil can be shunted until the adjustments are almost completed.

It will also be remembered that the instrument need not be of any particular design, since the final result is obtained with the needle undeflected; a galvanometer such as this can also be employed in several methods which have been devised for the comparison of electro-motive forces, in which the instrument is simply used to denote the *absence* of a current, and in which, therefore, the consequent advantages are the same as in the case of the Wheatstone bridge. Fig. 116 shows the connections for one such method, known as Lumsden's method.

E is the standard cell, and x the battery whose E.M.F. is to be measured. R_1 R_2 are two sets of resistance coils, and G is a

delicate galvanometer. A certain convenient resistance is introduced into the circuit by unplugging the necessary coils in R_1, and the resistance in R_2 is adjusted until the current ceases to pass through the galvanometer, thus showing that the two points, S and T, have been brought to the same potential. This being the case then

$$x : E :: R_2 : R_1,$$

therefore

$$x = \frac{E R_2}{R_1}.$$

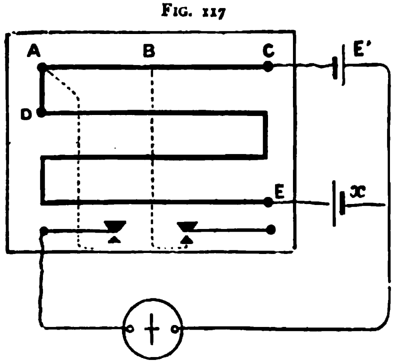
As an example, suppose the Daniell cell to be used as a standard, and R_1 fixed at 1000 ohms, while the potentials at S and T are equalised by making R_2 5650 ohms, then

$$x = 1{\cdot}079 \times \frac{5650}{1000} = 1{\cdot}079 \times 5{\cdot}65 = 6{\cdot}096 \text{ volts.}$$

It will be observed that the working out of this example is simplified on account of R_1 being made 1000 ohms. For this reason it is preferable to always make the resistance in the same arm as the standard cell some multiple of ten, and to obtain a balance by adjusting the other set of coils.

The horizontal galvanometer designed for use with the Wheatstone bridge answers very well for this test, and, as will be seen from fig. 117, the bridge itself may be used for the two sets of coils and then the usual key can be employed in the galvanometer circuit, while the 'infinity' plug between A and D can be used to break the battery circuit and so to minimise any error due to polarisation.

FIG. 117



When a delicate galvanometer is not available, R_1 and R_2 must be lower, but then the battery resistances become important and cannot be ignored. They may, however, be eliminated by increasing one of the resistances, say R_1, by a certain

amount, say P ohms, and obtaining a balance again by increasing R_2 by Q ohms.

Then $$x : E :: Q : P,$$

therefore $$x = E\frac{Q}{P}$$

The electro-motive forces are, in fact, simply proportional to the increase of the original resistances R_1 and R_2.

For example, if after one balance had been obtained, we were to increase the resistance R_1 by 500 ohms, and again obtain a balance by adding 2852 ohms to R_2; then $P = 500$ and $Q = 2852$, therefore

$$x = 1{\cdot}079 \times \frac{2852}{500} = 6{\cdot}155 \text{ volts.}$$

The proof of the method depends upon two laws demonstrated by Kirchhoff, which may be briefly explained.

Let the resistance R_1 (fig. 116) be slightly reduced, so that the balance is upset, then the currents in the three arms will flow in the direction indicated by the arrows.

The first of Kirchhoff's laws (which is almost self-evident in the present simple case) states that the current flowing to the point S is equal to the sum of the currents flowing from it, that is,

$$C_1 = C_2 + C \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1).$$

The second law declares that in any complete circuit, even when it forms part of a network, as R_1 E S T, the sum of the products of the current strength in each arm into the resistance of that arm is equal to the sum of all the electro-motive forces in the circuit. That is to say, if in each arm or portion of the circuit, the individual resistance of that arm is multiplied by the strength of the current flowing through that resistance, and if all the products so obtained are added together, then the sum so produced will be exactly equal to the sum obtained by adding together all the electro-motive forces in the various arms of the circuit.

The *algebraical* sum must, of course, be taken; for instance, if two currents, or two E.M.F.'s are opposite in direction, one must be reckoned as *plus* and the other as *minus*.

In the circuit R_1 E S T the only E.M.F. is that of the standard cell, which we denote by E, and, neglecting the internal resistance of this cell, we form the second equation thus :

$$E = C_1 R_1 + CG \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2),$$

G being the resistance of the galvanometer.

Similarly, in the circuit $R_2 x$ S T, the only E.M.F. is x, but the currents in the two arms are in opposite directions. Therefore

$$x = C_2 R_2 - CG \quad . \quad . \quad . \quad . \quad . \quad . \quad (3).$$

By inserting in (2) the value of C_1, given in (1), we get

$$E = (C_2 + C) R_1 + CG,$$

that is,

$$E = C_2 R_1 + C R_1 + CG \quad . \quad . \quad . \quad . \quad . \quad (4).$$

From (3),

$$C_2 = \frac{CG + x}{R_2};$$

and, inserting this value for C_2 in (4), we get

$$E = \frac{R_1 (CG + x)}{R_2} + C R_1 + CG;$$

$$R_2 E = C R_1 G + R_1 x + C R_1 R_2 + C G R_2;$$

therefore

$$C = \frac{R_2 E - R_1 x}{R_1 G + R_1 R_2 + R_2 G} \quad . \quad . \quad . \quad . \quad . \quad (5).$$

This equation gives us the value of the current flowing in the galvanometer circuit when the balance is upset, in terms of the various electro-motive forces and resistances. But in making the test we adjust so that no current flows through the galvanometer; therefore, when a balance has been obtained, $C = 0$, and, consequently, the fraction which forms the right-hand side of equation (5) is equal to 0.

Therefore, the numerator of the fraction

$$R_2 E - R_1 x = 0,$$

that is,

$$R_2 E = R_1 x, \quad . \quad . \quad . \quad . \quad . \quad (6)$$

and

$$x = E \frac{R_2}{R_1},$$

which proves the case when the battery resistances are so small as to be negligible.

Equation (6) holds good, in fact, so long as R_1 and R_2 represent the total resistance in their respective arms of the system.

When the resistances of the batteries cannot be ignored, they must be added to R_1 and R_2 respectively to make up the total resistance in the arm, and then equation (6) becomes

$$E\,(R_2 + r_2) = x\,(R_1 + r_1) \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where r_1 is the resistance of the standard cell, and r_2 that of the battery under test. Also, when R_1 is increased by P ohms, and R_2 by Q ohms,

$$E\,(R_2 + r_2 + Q) = x\,(R_1 + r_1 + P),$$

that is, $$E\,(R_2 + r_2) + E\,Q = x\,(R_1 + r_1) + x\,P \quad . \quad . \quad (8).$$

Subtracting (7) from (8), we btain

$$E\,Q = x\,P;$$

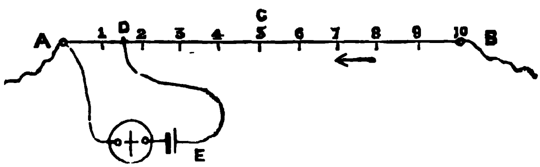
therefore $$x = E\,\frac{Q}{P}.$$

There are a number of methods for the comparison of electromotive forces, somewhat similar in principle to those just described. We have selected a few and worked them out at length, not only because they are in themselves interesting, but also because they involve, in a rather simple form, some very important principles and laws which the student will do well to master.

We will now direct our attention to a method based upon a somewhat different principle. In this case, again, no current passes through the galvanometer when the final adjustment has been made, thus permitting the use of a delicate instrument. But a further very great point in its favour is the fact that the batteries do not send any current while their E.M.F.'s are being actually compared. Consequently the Latimer Clark cell may be used as a standard to the best advantage, and the true E.M.F. of a battery subject to polarisation, like the Leclanché, can be measured; and further, since no current flows through the batteries or the galvanometer in the battery circuit, their resistances have no effect whatever, and need not therefore be known.

If between the ends A and B (fig. 118) of a uniform German-silver wire one metre (1000 millimetres or 39·37 inches) in length, a potential difference of 10 volts is maintained, the fall of potential will be uniform, say from B to A. Now it must be possible, under such conditions, to find a point in the wire such that the potential difference between that point and the end A shall be any desired fraction of 10 volts. For instance, between A and the middle of the wire, C, the difference is 5 volts. Furthermore, if the negative pole of the Clark standard cell E is joined to the point A, it will assume the same potential as that point, while the end of the wire connected to the positive pole will be 1·434 volt above that potential. A galvanometer may be joined up on either side of E without affecting the final result, and if the free end of the wire is joined to any point near B a current will flow through the galvanometer G in opposition to the standard cell, because the potential

FIG. 118



of the point near B is more than 1·434 volt above that at A; while, on the other hand, if contact is made at a point very near to A, where the potential is less than 1·434 volt, the standard cell will be able to maintain a current through the galvanometer and deflect the needle in the direction opposite to that which resulted from making contact at the point near B. Now, between these two positions a point, D, may be found where the needle will be undeflected, showing that no current is passing in either direction through the standard cell and galvanometer, and this point will be such that the difference of potential between it and A is equal to the maximum difference of potential which the standard cell can produce, viz. its E.M.F. of 1·434 volt. Since each of the ten equal parts into which the wire is divided represents a potential difference of one volt, the point D, at which a balance is obtained with the standard cell, should be nearly midway between 1 and 2. If the

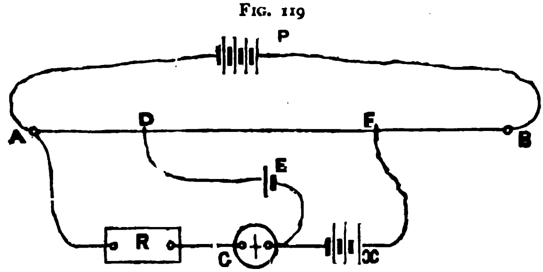
wire is perfectly uniform in resistance, the fall of potential will also be perfectly uniform, and the exact position of the balancing-point would then be 143·4 millimetres from A. This shows the advantage of having a wire divided into 1000 equal divisions.

As another example, suppose the standard cell were replaced by a battery of unknown E.M.F., we could readily find its E.M.F. by making contact at different points along A B until the absence of a current through the galvanometer indicated that a point had been touched where the E.M.F. is balanced. If this point were 970 millimetres from A, then the E.M.F. of the battery would be 9·7 volts. As we have remarked, the resistance of the galvanometer and battery may be high and yet not affect the final result. The only objection to high resistance is that when the balance is nearly, but not quite, obtained, the potential difference tending to send a current through the galvanometer is very small, and if the resistance in the galvanometer circuit is very high the resulting current will be weak and may not be able to cause a perceptible deflection of the needle. This would prevent the balancing-point being found exactly, and it is therefore a good plan, in order to avoid such want of sensitiveness, to employ a very delicate galvanometer, and place a set of high resistance coils in circuit with it. At first all the resistance should be unplugged; it can then be reduced (by plugging up) as the adjustment becomes approximately correct, the final adjustment being made with all the resistance out of circuit. Injury to the galvanometer may thus be avoided, and the greatest possible degree of accuracy attained.

It is clear that if we could with certainty maintain a constant potential difference between the extremities of the graduated wire, no standard cell would be required, and it would be very convenient to be able to measure E.M.F.'s as simply proportional to a certain length of the wire. It is difficult, however, to maintain any given difference of potential between two points for any length of time, and therefore in practice a slightly different arrangement from that just described is adopted. A current is sent through the wire A B (see fig. 119) from some fairly constant generator, P, such as a good low resistance battery or a few of the 'secondary cells' to be described hereafter, sufficient to maintain between A and B a potential difference greater than that of the highest E.M.F. to

be measured. The wire is stretched over a scale divided into a thousand parts, and therefore, if of uniform gauge and material, the fall of potential along one of these units is equal to a thousandth part of the fall along the whole wire. The Clark cell, E, and the battery to be measured, x, are joined up with their negative poles connected through a galvanometer, G, and a set of resistance coils, R, to the point A, as shown in fig. 119. Their other poles are connected to sliders, by means of which contact may be quickly made with any point along the wire. The whole of the resistance is put in circuit at first, and the slider connected to the standard battery is shifted along until a point is found where the deflection on the galvanometer is very slight when contact is made with the

FIG. 119



wire A B. The resistance R is then gradually reduced until the exact point (D) is found. The distance from A to D must be carefully noted, and then a point, F, at which the E.M.F. of the battery x is balanced, is found in a similar manner. Now, the potential difference between A and D is equal to the E.M.F. of the standard cell—that is, 1·434 volt—and the potential difference between A and F is equal to the E.M.F. of the battery x. Therefore

$$AD : AF :: E : x.$$

Suppose A D to be 120, and A F 685, divisions ; then

$$120 : 685 :: 1{\cdot}434 : x;$$

therefore $$x = \frac{685 \times 1{\cdot}434}{120} = 8{\cdot}19 \text{ volts}$$

It will thus be seen that it is unnecessary to maintain any particular potential difference per unit of length of the wire, for this can be readily found by means of the standard cell. But it is advisable, after the adjustments have been made as above, to verify the result by making contact with both sliders at almost the same moment, in order to ascertain whether or not the fall of potential has varied during the test.

In fact, one great feature in favour of this arrangement is that the test may so be made that a slight variation of the potential difference at the ends of the stretched wire need not cause any error; the source of inaccuracy which has most to be guarded against is a want of uniformity in the wire itself. By using a *low* resistance battery a greater proportion of the fall of potential takes place in the external circuit—that is, along the stretched wire—than when a high resistance battery is employed; hence the suitability of secondary cells for this purpose. A greater length of wire may be conveniently obtained by stretching it backwards and forwards several times upon a board. An instrument based upon the foregoing principles for measuring potential differences is commonly called a potentiometer. The wire is sometimes wound in a spiral groove round an ebonite cylinder, and, when made in this form, it can easily be divided into 20,000 parts, but this type is rarely used for practical work.

A very ingenious and useful development of the principle is involved in Crompton's potentiometer, which is designed for measuring relatively high potential differences, such, for example, as are in general use for public lighting and power services. Fig. 120 illustrates the arrangement. A B are the mains carrying the current whose potential difference it is desired to measure. These are connected by wires to *b b*, which are the ends of a long and high resistance wire, and of which *c c* is a known and definite fraction, say one-hundredth or one-thousandth part. E E is the equivalent of the potentiometer wire—that is to say, it is a wire of uniform gauge and of high specific resistance, and is connected to an approximately steady source of E.M.F., such as a secondary cell or battery. There is therefore a uniform fall of potential along this wire. S is a standard cell, such as the Clark or the Cadmium cell, which is joined in series with the galvanometer

K may now be moved so as to bring the levers on to the second blocks of X Y, and Q R moved until no deflection of G is obtained on the full depression of L. Let us suppose that this results when Q is on 1·2 and R is on ·07, then the potential difference between M N will be 1·27 volt, and if the blocks of X Y are connected to a resistance coil which (corresponding to *c c* of fig. 120) absorbs one-hundredth part of the E.M.F. to be measured, it follows that that E.M.F. is 127 volts. If, however, the blocks on X Y represent only one-thousandth of the potential difference to be measured, and a zero reading of G is obtained when Q is on ·6 and R is on ·01, the E.M.F. between X and Y is ·61 and the total E.M.F. of the circuit in question is ·61 × 1000 = 610 volts.

The instrument is not in the ordinary sense of the word direct reading, but it is so carefully made, and the operation is so simple, that it can easily be used as a standard instrument for the calibration and verification of other and mechanically simpler forms of apparatus which can be used for direct-reading purposes. It may also suggest itself to the student that by making the resistance corresponding to *c c* fig. 120 of substantial dimensions, the principle can be applied for the purpose of measuring current strength. In the actual instrument a number of refinements are introduced which we need not detail, but it is interesting to note that when the resistances are adjusted so as to give values in volts direct, the maximum range is 1·5 volt reading in thousandths of a volt, and by inspection to ten-thousandths.

In all the preceding methods potential difference is measured indirectly or by comparison with a standard. Instruments have, however, been devised which indicate directly, in volts, the difference of potential between any two points; such instruments are called voltmeters. That invented by Major Cardew is simple in principle, depending upon the elongation of a wire when heated by a current, and although it is not now used in practice to any appreciable extent, the principle is sufficiently instructive to warrant a detailed description.

If a wire is heated it increases in length. This linear expansion or extension is proportional to the product of the rise in temperature and the coefficient of expansion for the particular wire. The coefficient of linear expansion is defined as the

elongation of a body of unit length when its temperature rises from zero to one degree (Centigrade), and this coefficient or proportional extension in the case of platinum, for example, is 0·0000088, so that, for an increase in temperature of 10° C., a yard of platinum wire would be extended to 1·000088 yard. By measuring the amount of extension produced by heating a wire, the increased temperature can therefore be inferred, and this is the basis on which the Cardew voltmeter was designed.

Now, when a current of electricity passes through a wire it performs a certain amount of work in overcoming its resistance, and the generation of heat is the result. The rise in temperature resulting from the generation of a certain amount of heat does not, however, bear a simple ratio to that amount of heat. It depends, in fact, upon the time or duration of the current, and upon the specific heat or calorific capacity of the particular substance. The former of these factors is so very apparent that we need not further enlarge upon it. The specific heat of a body is defined as that quantity of heat which it absorbs when its temperature rises through a given range—say from zero to 1° C.—as compared with the quantity of heat which would be absorbed by an equal mass of water when its temperature is exalted through the same range. If, for example, a pound of mercury at 100° C. is mixed with, or placed in, a pound of water at zero, the temperature of the mixture will be only 3° C., so that, while the mercury has lost 97°, the equal mass of water has only increased 3°, or, in simple language, a quantity of water absorbs about thirty-two times as much heat as an equal weight of mercury, in undergoing the same exaltation of temperature. The specific heat of water being taken as unity, that of mercury is in fact 0·03332. Similarly, the specific heat of platinum is 0·03244.

The variation in the temperature of a wire due to an increment or decrement of heat depends also upon its weight or its sectional area, for it will be evident that if two wires of similar material and of equal resistance, but of different gauge or different weight—such, for example, as a given length of platinum wire weighing one gramme, and another platinum wire, twice as long, but weighing four grammes (offering, therefore, equal resistances)—have the same current passed through them, they will not be raised to the

same temperature, although the amount of heat actually developed will be the same in each case. This follows from the fact that in the one case there is more material to heat than in the other.

When a current of electricity passes through a wire, and, as we have said, performs a certain amount of work in overcoming its resistance, the equivalent of the quantity of energy absorbed in the performance of this work is seen in the development of a definite amount of heat which is imparted to the wire. The heat (H) developed in a unit of time is, in fact, directly proportional to the amount of power expended in overcoming the resistance of the conductor—that is to say, it is proportional to the product of the difference of potential, E, between its extremities, into the strength of the current, C, which is maintained through it; or H varies as $E \times C$. If, however, the resistance of the wire remains constant, the value of C varies directly as E; consequently by doubling E, C is also doubled, and the heat developed varies therefore as the square of E.

Again, the heat unit is defined as that amount of heat which is required to raise 1 gramme of water through 1° C. in temperature, and a potential difference of 1 volt maintained through a resistance of 1 ohm develops 0·24 such heat units per second—that is to say, the number of heat units, H, developed in t seconds, is

$$H = 0{\cdot}24 \times E\,C\,t.$$

As $E = C\,R$, it follows that $E\,C = C^2\,R$, so that the formula may also be expressed by saying that

$$H = 0{\cdot}24 \times C^2\,R\,t.$$

Collecting all these facts into one simple formula, where T° represents the rise in temperature in Centigrade degrees, E the potential difference in volts, C the current strength in amperes, t the time in seconds, h the specific heat, g the weight of the metal in grammes, and 0·24 the constant which, as pointed out above, is necessary to obtain a result on the Centigrade scale, we may say that

$$T^\circ = 0{\cdot}24 \times \frac{E\,C\,t}{g\,h} = 0{\cdot}24 \times \frac{C^2\,R\,t}{g\,h};$$

so that in the ideal (but actually impossible) case of a current of 1 ampere flowing for 1 second through 1 gramme of water (whose

specific heat is 1·0), and offering 1 ohm resistance, involving, therefore, a potential difference of 1 volt, the water would, if all the energy expended were devoted to the generation of heat, be raised 0·24° C. in temperature.

Similarly, if the same current were maintained through a platinum wire of the same weight and resistance, the increase of temperature would be

$$T^\circ = 0{\cdot}24 \times \frac{E\,C\,t}{g\,h} = 0{\cdot}24 \times \frac{1 \times 1 \times 1}{1 \times 0{\cdot}03244} = 0{\cdot}24 \times \frac{1}{0{\cdot}03244}$$
$$= 7{\cdot}4^\circ \text{ C., nearly.}$$

The coefficient of linear expansion for platinum being 0·0000088, it follows that with a wire 100 inches long the elongation produced by an increase in temperature from 0° C. to 7·4° C. would increase the length of the wire to

$$100 + (7{\cdot}4 \times 100 \times 0{\cdot}0000088) = 100{\cdot}006512 \text{ inches.}$$

In the Cardew voltmeter a length of very fine platinum-silver wire is employed, and is heated by the passage of the currents whose E.M.F. it is desired to test. In each test, therefore, g and h retain the same values, and by limiting the increase of temperature between the points of lowest and highest reading to a few degrees, the very slight variation of R also becomes a negligible quantity. Similarly, by employing a fine wire, it speedily rises to such a temperature that, with any given current, the loss of heat due to radiation equals in amount that which is developed by the current. The only really variable quantities, therefore, are E and C. But, as already pointed out, C varies uniformly with E, and if the facilities for radiation remain the same, the increase of temperature, and with it the elongation, will always be the same for any given value of E. Hence, the amount of elongation can be made to indicate the potential difference maintained between the extremities of the wire.

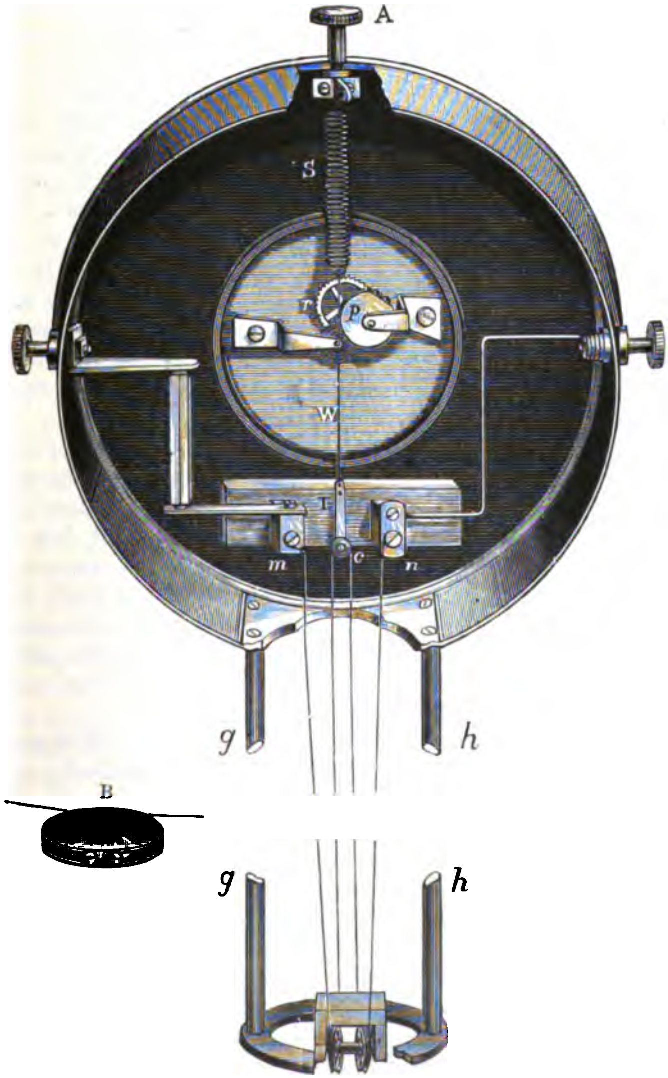
Simple as the principle is, the construction of a reliable practical instrument proved to be a matter of considerable difficulty, and an enormous amount of experimental work was performed in determining the sources of error to which a Cardew voltmeter was liable. Fig. 122 illustrates one form of this

instrument. The outer casing is removed to show the essential parts as viewed from the back.

The platinum-silver wire is 0·0025 inch ($2\frac{1}{2}$ mils) in diameter, and is fixed at one end to the small brass block *m*. Thence it is led round one of two grooved pulleys supported by a ring at the ends of two metal rods, *g h*, which are about 36 inches long, and are fixed to the brass base-plate. From this pulley the wire returns, and is passed round a small pulley, *c*; thence it is led to the second pulley at the top of the rods, and is finally terminated at the small brass block *n*. The brass pieces *m* and *n* are supported by the insulating block of varnished vulcanised fibre, which is securely fastened to the brass base-plate, and *m* and *n* are connected each to one of the main terminals of the instrument, which are insulated by ebonite or fibre collars from the brass casing. The wire passes round the pulleys at the top of the rods in such a manner that a pull at *c* on the two centre wires causes both pulleys to rotate in the same direction, and, the spindle being pivoted in jewelled holes, the friction is reduced to a minimum.

The small part, *c*, referred to as a pulley, only acts as such during the wiring of the instrument, as the extension of the wire when the apparatus is subsequently used does not cause it to rotate. It is made of vulcanised fibre, with a small groove round its circumference in which the wire lies, and is fixed by a small screw passing loosely through its centre to one end of the thin brass strip T, the other end of which has attached to it a fine platinum-silver wire, W, connected to the spiral spring S. The tension of this spring, which can be varied by means of the adjusting screw A, keeps the wires taut, and when the main terminals are connected to points in a circuit at different potentials, a current passes—say to the block *m*—up the wire, and round the first pulley back to the insulating reel *c*; thence again to the top of the instrument, round the second pulley, and back by way of *n* to the other terminal. This current heats the wire, which expands, and the slack is immediately taken up by the spiral spring S, so that the small brass strip T and the wire W are moved through a distance equal to the expansion of *two* lengths of the heated wire. The amount of expansion (and therefore of the potential difference

FIG. 122



applied) is measured by observing the distance through which the length of wire W is moved; but, as this distance is, at the most, extremely small, some mechanical multiplying arrangement is necessary, and, since the force producing the movement is also very feeble, care has to be exercised in avoiding the introduction of any appreciable friction. These results are attained by the use of a jewelled watch movement. The wire W is led round a small pulley, *p*, fixed upon the same spindle as a toothed wheel, *r*, which gears into a small pinion, the spindle of which carries a long needle or pointer, passing over a scale-plate at the back of, and not visible in, the figure. When the wire is extended by the current, the spring S causes the pulley *p* to turn through a small angle, and with it also the wheel *r*, the pinion, and the pointer; and, as the diameter of the wheel is much greater than that of the pinion, the pointer is turned through a large angle by a comparatively small extension of the wire.

The passing of the wire W round the pulley so as to get a reliable grip, and at the same time avoid friction or risk of damage to the fine wire, is a more difficult matter than might at first sight appear. The pulley is shown separately at B. It has two narrow parallel grooves round its circumference, at one part of which (where it is filed away flat) two set-screws are fixed, both screwed up home. The wire is led from T round the first groove to the screw-heads, between which it passes over to the second groove, in which it completes its journey round the pulley, and is then led to the spiral spring.

The wire is so fine that it would not bear being pinched under the screw-heads, but the arrangement described effectually overcomes any tendency to slip; and as the pulley only moves through a small angle, never making a complete revolution, no sensible friction is introduced. Considerable importance attaches to the shape of the spiral spring S and to the material of which it is composed. It is necessary that the tension of this spring should remain constant; and the difficulty has been surmounted by (*a*) choosing a spring little liable to vary, spiral in form, and of German silver, and (*b*) providing a thumbscrew A on the outside of the case, by turning which the pointer can, in the event of any variation, be readily restored to zero.

Although there are four straight lengths of wire equally heated, it will be remembered that, since *c* does not rotate, the elongation measured is equal to that of only two lengths, for the movement would be the same as if one of the wires were rigidly fixed to it and the other removed. But it will be noticed that the tension due to the spiral spring is equally distributed between the two wires leading from *c*, and this affords the advantage that double the tension can be given to the spring, which means that the force with which the pulley *p* is turned can be doubled, and any slight error due to friction correspondingly reduced, without, at the same time, necessitating the adoption of a comparatively thick wire. The wheel work is well made, but it is, of course, impossible to altogether avoid 'back lash'—that is to say, as the teeth of the driving-wheel do not fit tightly between the teeth of the pinion, the latter does not begin to move absolutely at the same moment that the driving-wheel does when the motion of the latter is reversed. To avoid the slight error which this might cause, a hair-spring is fixed to the pinion spindle. This spring is visible in fig. 122, the pinion being immediately behind, and therefore hidden by it. It is adjusted so as to maintain sufficient pressure between the teeth of the wheel and pinion to keep them always in contact, so that in either direction the two move simultaneously.

The whole of the casing is of brass; but the rods (*g h*, fig. 122) cannot be made of that metal, as, its coefficient of expansion being higher than that of platinum-silver, it would expand more than the wire with any rise of temperature, atmospheric or otherwise, and cause a deflection of the pointer. On account of the expense, platinum-silver cannot be employed for these rods. Iron has, however, a lower coefficient of expansion than the wire, and the rods are therefore made partly of iron and partly of brass, the length of these parts being so proportioned that the greater expansion or contraction of the brass shall be neutralised by the lesser expansion or contraction of the iron, and the whole rod vary in length in exactly the same proportion as the wire itself. The wires are encased throughout their length by a brass tube, which can be removed, and the arrangement of the pulleys, together with an opening in the supporting ring to which they are attached,

facilitates the re-wiring of the instrument. In order to prevent damage to the working wire by the accidental passage of a too-powerful current, a safety fuse is inserted in series with it, consisting of a short length of platinum-silver wire, 0·0014 inch ($1\frac{2}{5}$ mils) in diameter, which fuses and breaks the circuit before the current attains sufficient strength to fuse the thicker working wire. This fuse-wire is placed in a saw-cut along the face of a rectangular strip of vulcanised fibre, each end being terminated at a round-headed brass screw in the end of the block, which is firmly held between two flat springs making contact with the screw-heads, one spring being connected to *m* and the other to the left-hand terminal. Connection between *n* and the other terminal is made by a stout, stiff wire.

The voltmeter illustrated is capable of measuring from 30 to 120 volts. As it is the heating of the wire which affords a measure of the electro-motive force, the 'heating-error' peculiar to most of the voltmeters in use when the Cardew was designed is here entirely absent. For the same reason, the reading is unaffected by the presence of external currents or any electro-magnetic field, and, as iron is not employed and the wire is not coiled, its self-induction is practically *nil*. Hence, alternating potential differences can be measured; but it must be remembered that this same absence of self-induction in the instrument, in allowing a current to rise suddenly to its full value, limits the range through which the fuse can protect the working wire; for although the fuse acts with certainty if the current rises at all gradually, a very sudden application of a very high E.M.F. would develop a heavy current instantaneously, fuse and wire being melted simultaneously, and this was one of the main causes which led to the substitution of instruments of other types. Another reason was the size of the instrument and the inordinate amount of space occupied.

Although the instruments are made to register up to 120 volts only, the values of the readings can be increased by inserting in the circuit, in series with the voltmeter, resistance coils of various multiplying powers. Thus, if a coil equal in resistance to the wire in the voltmeter were introduced, it would exactly halve the potential difference of the circuit at the terminals of

the voltmeter due to any particular E.M.F. Manifestly, such a coil would have a multiplying power of two, while a coil of three times the resistance would reduce the proportion of potential difference absorbed by the voltmeter to one-fourth, and therefore have a multiplying power of four. These resistance coils, however, must not be of the ordinary type. The wire should be of platinum-silver, of the same gauge as in the voltmeter, and in order to produce equal facilities for radiation it should be bare, and, for convenience, it may be stretched in tubes similar to those employed in the voltmeter itself, or it may be stretched over a rectangular framework made by attaching two rods of slate to a couple of strips of wood or iron, notches being made in the slate to receive the wire and prevent one portion slipping into contact with another. The wire and framework are in the latter case enclosed by pieces of thin sheet iron.

The ordinary Cardew voltmeter is not suitable for the indication of low potential differences, owing to the exceedingly small elongation due to the slight rise in temperature, and the consequent vagueness of the readings which would result therefrom. Several modifications have been devised for this purpose by the original inventor and by a number of others, prominent among whom were Professors Ayrton and Perry, whose instrument was capable of indicating small fractions of a volt. These instruments in common with other 'hot-wire' voltmeters, have, however, now fallen into disuse, and as the underlying principle was the same in all of them, further descriptions are perhaps unnecessary.

We come now to a consideration of the means adopted to convert the instruments which we described in Chapter IV. as available for the measurement of current strength, and which are called ammeters, so that they can be employed as voltmeters.

An ammeter measures directly the strength of the current flowing through its coils, and this current is proportional to the difference of potential at the terminals of the instrument. It might, therefore, at first sight appear that any ammeter could be used to measure the potential difference between any two points by simply joining it up to them, observing the strength of the current flowing, and from that inferring the difference of potential

which maintains it. It is evident that to measure the potential difference between two points it is essential that the terminals of the instrument should be joined directly to those points. But the very act of connecting two points in a circuit by a low resistance ammeter would alter the distribution of the potential difference considerably. Let us suppose, for example, that it is desired that an instrument of low resistance shall be used to measure the electro-motive force of a primary battery, of appreciable internal resistance. Then the potential difference which is measured by joining the instrument to the terminals of the battery is not equal to the E.M.F. of the battery, but only to the fall of potential through the instrument, and this fall will bear to the E.M.F. of the battery the same proportion which the resistance of the instrument bears to the resistance of the battery. If, for example, the E.M.F. of the battery is 50 volts and its internal resistance 99 ohms, while the resistance of the ammeter is, say, for simplicity sake, one ohm, then the total resistance in circuit will be 100 ohms, and, remembering what was said in the concluding pages of Chapter III., the student will perceive that as the external resistance is only $\frac{1}{100}$ of the total, only $\frac{1}{100}$ of the E.M.F. will be expended upon that resistance. In other words, the potential difference which will be measurable will be only $\frac{1}{100}$ of the total E.M.F., or $\frac{50}{100} = 0{\cdot}5$ volt, the remaining $49{\cdot}5$ volts being absorbed in overcoming the resistance of the battery itself. Again, if the battery is already supplying current to any particular circuit, and it is desired to measure the potential difference at the terminals of that circuit, the measuring instrument would have to be joined across the terminals of the circuit, and would therefore form a shunt to it, and if the instrument had a low resistance it would manifestly reduce the strength of the current flowing through the original circuit; or, in other words, the very act of joining up the instrument to measure the potential difference would lower that potential difference which it is desired to measure.

Consequently, although the ammeter so placed might correctly indicate the potential difference between the two points *after* they

were so joined, it would give no information as to their condition before. For instance, if a piece of German-silver wire, having a resistance of 5 ohms, forms part of a circuit through which a current of 4 amperes is flowing, we know, since $E = C \times R$, that the difference of potential between the extremities of the wire is $4 \times 5 = 20$ volts. If we proceed to measure these volts, by connecting an ammeter having a fraction of an ohm resistance to the ends of the wire, we shall, assuming the remainder of the circuit including the battery to have an appreciable resistance, get much less than 20 volts, for the resistance, and therefore the fall of potential, in that portion of the circuit, will have been considerably lowered. Although the total current in the main circuit will be increased by this lowering of the total resistance, the ammeter resistance is so low that it shunts the greater part of the current from the German-silver wire; and supposing that, in consequence, only half an ampere flows through that wire, the potential difference at its ends will be $C \times R = {\cdot}5 \times 5 = 2{\cdot}5$ volts only, instead of 20, and of course there would be this decreased potential difference at the terminals of, and indicated by, the ammeter. There is, however, another consideration which will no doubt prove instructive: let us assume that the German-silver wire is joined direct to the terminals of a dynamo or secondary battery of very low resistance, and of sufficient electro-motive force to maintain a potential difference of 20 volts at the extremities of the wire even when we also join to the terminals referred to one of the ampere gauges described in Chapter IV. Let the instrument be capable of carrying and indicating 250 amperes of current, and let it be assumed that the power absorbed is ten watts. Now the number of watts (W) is equal to $E \times C$, or

$$W = EC = E \times 250 = 10$$

therefore $$E = \frac{W}{C} = \frac{10}{250} = 0{\cdot}04 \text{ volt},$$

that is to say, the difference of potential between the terminals of the instrument when it is carrying the full current of 250 amperes is only 0·04 volt, but resistance is equal to $\frac{E}{C}$, that is, to the poten-

tial difference divided by the current which that potential difference can maintain ; therefore the resistance of the instrument is

$$R = \frac{E}{C} = \frac{0{\cdot}04}{250} = 0{\cdot}00016 \text{ ohm.}$$

It follows that if we were able to maintain a potential difference of 20 volts across the terminals of such an instrument the current would be

$$C = \frac{E}{R} = \frac{20}{0{\cdot}00016} = 125{,}000 \text{ amperes.}$$

An instrument capable of carrying such a current has not yet been made, neither has the dynamo or battery been constructed which would be capable of developing such a current. The result of joining up the ammeter in the way suggested would result in the burning up of the instrument, unless the dynamo happened to succumb first.

Obviously, in order that the introduction of the instrument should make absolutely no alteration, no current at all should flow through it; and although, as we shall see presently, there are instruments which satisfy this condition, some of them are only suitable for use in the laboratory. If, however, we take any ordinary ammeter, and wind it with a large number of turns of fine wire, so that it has a very high resistance, it can be used as a voltmeter; for its resistance will be too great, and the current which passes through it will be too small, to make any sensible alteration in the potential difference which it is measuring; while, on the other hand, the large number of turns of wire will allow the feeble current so flowing to produce a sufficiently strong magnetic field to actuate the movable part of the apparatus. For instance, one of the 'gauges,' described in Chapter IV., when wound with fine wire to a resistance of about 2000 ohms, will serve to measure potential differences of from 60 to 120 volts. In this connection the student may perhaps be reminded that the field developed in the neighbourhood of the 'moving iron' is proportional to the ampere-turns, or to $C\,t$. If it is assumed that the power absorbed by the instrument is to be limited to 6 watts, and that the potential difference which the instrument is to

measure is to be 100 volts, the current which it will carry at that pressure will be

$$C = \frac{W}{E} = \frac{6}{100} = 0{\cdot}06 \text{ ampere,}$$

and similarly its resistance will be

$$R = \frac{E}{C} = \frac{100}{0{\cdot}06} = 1666 \text{ ohms.}$$

We are now in a position to determine the size and length of wire which will meet these requirements. The first point to determine is the current-density which shall be permitted—that is to say, the proportion which shall exist between the current and the size of conductor conveying it. This is usually indicated by the current which a rod having a cross-section of one square inch would carry, and we will assume for our present purpose that the current density may be as high as 2000 amperes per square inch of cross-section. If our current to be carried were one ampere, the cross-section of the wire would therefore have to be $\frac{1}{2000}$ square inch, but being only 0·06 ampere the cross-section need be only $\frac{0{\cdot}06}{2000} = 0{\cdot}00003$ square inch. If reference is now made to the table given in Chapter XVII., it will be seen that the nearest available wire to this is No. 38 S.W.G., which has a cross-section of 0·00002827 square inch, and that a mile of this wire offers a resistance of 1496 ohms, and weighs 0·5754 lb. We should therefore require $\frac{1666}{1496} \times 1760 = 1960$ yards of this wire. Let us next assume that the instrument, being of the same type as those referred to in Chapter IV., requires for the development of its maximum field a magnetising force of 300 ampere-turns, or

$$t = \frac{300}{C} = \frac{300}{0{\cdot}06} = 5000 \text{ turns.}$$

Referring once more to the table, it will be seen that the diameter of the wire is 0·006 inch, and allowing 0·0025 for the double thickness of silk with which the wire may be covered for insulating purposes, making a total thickness of 0·0085 inch, the required number of turns, viz. 5000, could be provided on

a bobbin in which the coil space (see page 263, Chapter VII.) measures 1 inch × 0·3655 inch.

The bobbin will have to carry 43 layers of wire (with about 117 turns in each layer), and the thickness or depth of the coil will therefore be 0·3655 inch. If we assume that the diameter of the bobbin is 0·75 inch, or the radius 0·375 inch, the average length of each turn of wire will be $2 \pi r = 2 \pi \times (\frac{0{\cdot}3655}{2} + 0{\cdot}375)$ $= 3{\cdot}5047$ inch, and the total length of wire on the bobbin will be about 17,523 inches. The remaining 53,000 inches, or its equivalent in German-silver wire, will have to be wound on a separate bobbin and joined in series with the coil. If the coil were made of larger diameter, the length of wire to be wound on it would be correspondingly increased.

All such voltmeters require to be calibrated for reading in volts, in the same way that the ammeter was calibrated for reading in amperes.

One important source of error must, however, be guarded against; it is due to the fact that a current, in passing through the coils of a voltmeter, heats the wire and increases its resistance, and consequently a given difference of potential will send a weaker current through the coils after they are heated than before. The instrument will therefore indicate a lower difference of potential than that which actually exists, in consequence of the fact that it measures the potential difference by the strength of the current set up by that difference. For this reason a wire which is thicker and therefore longer than would otherwise be necessary is frequently used, and in many instances efforts are made to facilitate radiation and ventilation, and thereby to keep the temperature tolerably uniform. In fact, no effort should be spared to prevent the coils of a voltmeter being heated to any appreciable extent by the current. A considerable heating error may even be caused by the relatively high temperatures of many engine-rooms. This arises from the fact that moving-iron voltmeters are wound with copper wire, which, it may be remembered (see p. 20), increases in resistance 0·29 per cent. per degree Centigrade increase of temperature; and supposing the instrument to have been calibrated at a temperature of, say, 15° C., it is easy to

imagine a state of affairs which would cause an increase of 5 per cent. in the resistance of the instrument, and a correspondingly smaller current to flow through it, when a certain potential difference is applied at its terminals. Under such circumstances the instrument will indicate lower voltages than it should do. It would be possible to get over the heating error due to the current by having a small switch in circuit with the voltmeter, and only placing the instrument in circuit when it is desired to take a reading. This can, of course, be done by closing the circuit with the switch and taking the reading before the wire has had time to get hot. If, however, the instrument is required to be kept permanently connected up, it is advisable to have it calibrated to indicate correctly under such conditions, and this may be done by keeping the current on for, say, half an hour before noting the readings at the various points on the scale. The indications of an instrument so calibrated will, of course, assuming it to have been allowed to get cold, be rather too high immediately after it is connected up. It is, however, much preferable to so construct the instrument as to avoid as far as possible any prejudicial effect due to heating. The use of German silver for a large proportion of the wire is one way of getting over the difficulty.

In the case of a moving-iron *ammeter* the resistance of the coil is usually very low, and, the size of the wire being comparatively great, the temperature, and therefore the resistance, varies but slightly, except at or near the highest indication on the scale. Many ammeters, of course, get warm if the strongest currents for which they are constructed are maintained through them for any considerable time. An ammeter, however, is placed directly in the circuit, and it is virtually free from the 'heating-error,' because, under all circumstances, the strength of the current flowing through it and measured by it is the same as that in the rest of the circuit.

In the case of Evershed's moving-iron voltmeter, or volt gauge, the moving parts are exactly similar to those of the ampere gauges shown in figs. 72 and 73, but, of course, thin wire, offering high resistance, is employed. Only a portion of this wire forms the actual magnetising coil, this being of copper, while the remainder, which is of silk-covered platinoid wire, is wound on a vulcanised

fibre frame which is fixed inside the casing. In an instrument indicating up to 110 volts the total resistance would be rather over 2000 ohms (that of the actual magnetising coil being about 200 ohms), so that, with the maximum potential difference, the power absorbed is only 6 watts; the magnetising coil having an effective power of about 500 ampere turns. As the temperature coefficient of platinoid is low, and the disposition of the wire gives fairly good facilities for radiation, its resistance does not rise appreciably. Consequently, the instrument may be left continually on the circuit without causing any serious error under ordinary working conditions.

The outer iron sleeve, which, it will be remembered, fits friction-tight on the brass tube, is the principal adjustable part of the instrument; by turning it round so as to vary the force with which the needle is acted upon at different points, the scale may be made open or close at any desired part.

Dealing next with the moving-coil voltmeters, which are, like the ammeters described in Chapter IV., all based on the so-called D'Arsonval galvanometer principle, and consist essentially of a small coil of fine wire suspended in the two small gaps which separate the poles of a permanent magnet from a soft-iron cylinder fixed between those poles. The air-gaps being small and comparatively extensive the magnetic field in which the coil moves is at any particular moment uniform. The resistance of the coil is, however, low, and is therefore unsuitable for joining direct to the terminals of a dynamo or other source of current. Resistance coils have in consequence to be joined in series with the moving coil. The instruments being of the polarised type—that is to say, with a permanent field set up by an independent magnet—are only suitable for measuring direct currents or potential differences.

In the Weston voltmeter the movable coil of copper wire is wound on a rectangular copper frame and has a resistance of about 60 ohms, and a full deflection is produced when a potential difference of about 0·6 volt is directly applied to this coil. The resistance coil, which is inserted in series with the working coil, has a value proportional to the value of the maximum potential difference it is desired to measure. This value is calculated at the

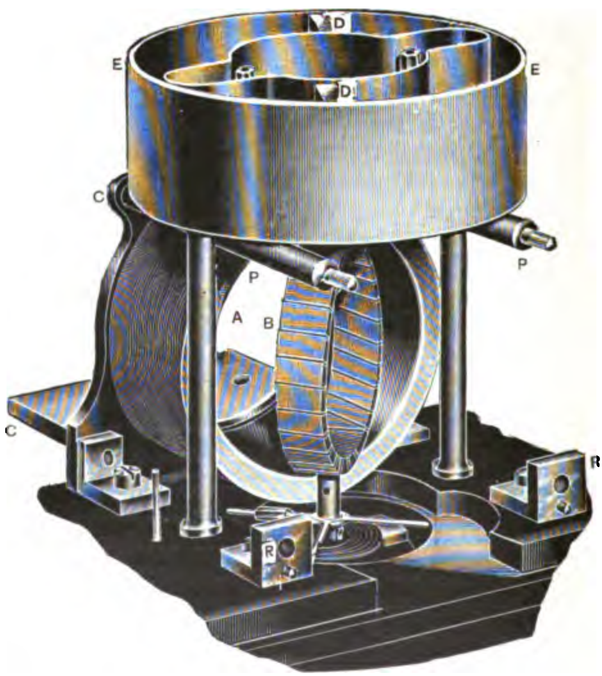
rate of 100 ohms to every volt above 0·6 volt. For example, about 16,600 ohms would have to be inserted in series with an instrument required to indicate up to 100 volts. This resistance for ranges up to about 600 volts takes the form of a coil of platinoid or manganin wire placed under the same cover as the working coil, and since by far the larger proportion of the resistance in the voltmeter circuit consists of an alloy with a very low temperature coefficient, the temperature error of the instrument is inappreciable. It can therefore be kept continuously in circuit, and the very high resistance used in series with it makes the loss of power very small. For instruments of over 600 volts the resistance coils are placed in a separate case, and such coils can readily be employed as 'multipliers,' that is to say, the coils can be tapped at various points by the use of suitable terminal screws, and the range of the voltmeter varied at will, by inserting resistances of various known values in series with it.

It will doubtless be remembered that all the ordinary moving-coil instruments are of the polarised type and only available therefore for direct-current circuits. Fig. 123, however, illustrates the working parts of a Weston instrument, which is suitable for measuring alternating potential differences. Its construction is based on the same principle as the Siemens dynamometer. The fixed coil consists of two halves, of which one is shown at A in the figure. It is supported by the bracket C. The other half has been removed to render the interior of the instrument clearer. It is supported by a bracket similar to C, which is clamped at the top to the ends of the rods P P, and at the bottom to the small angle pieces R R. The moving coil B is delicately pivoted in hard sapphire jewels between the two halves of the fixed coil. The moving coil carries a pair of very thin aluminium vanes, D D, weighing only three or four grains. These vanes work in a pair of closed air-chambers E E and are therefore very effective as dampers. As in the case of the dynamometer, the fixed and moving coils are joined in series, so that the same current passes through both, and the deflection is dependent upon the strength of the current only, and not upon its direction. The instrument is dead-beat and free from error due to self-induction or magnetic reaction. It is carefully calibrated by checking it against a reliable

standard, which in its turn is checked against a potentiometer and a Weston standard cell.

We have remarked that the ideal voltmeter is one which only indicates potential difference and does not allow any current to pass through it—that is to say, its resistance should be infinite so that there would be no fall of potential in the instrument

FIG. 123



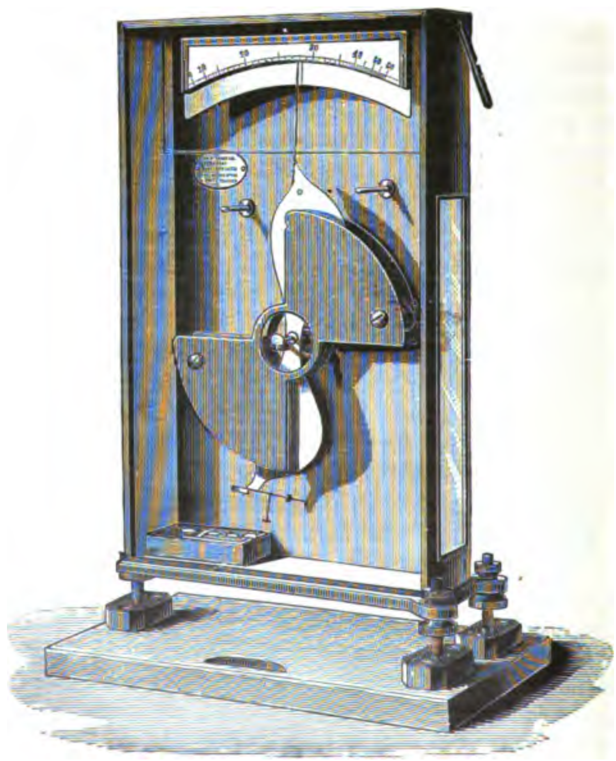
itself consequent upon the passage of a current. It would not be quite correct to say that there is no consumption of electrical energy, because something must be moved in order to change the position of the indicating needle, and as we shall presently see, this something takes the form of one or more light metallic vanes. The work done in moving these is very trifling, but such as it is, it must be at the expense of the electricity, the electro-

motive force of which it is desired to measure. Instruments of this type are 'electrostatic,' and the energy is derived from the brief but certain rushes of electricity into the instrument necessary to raise its several parts to the desired difference of potential. As soon as we cease to depend upon electromagnetic effects we free ourselves from any inconvenience due to heating error, because there are no coils to heat; and, because there are no coils, we have no risk of self-induction. The absence of magnets, either permanent or induced, also gets rid of other sources of error. Unfortunately, as we shall see presently, electrostatic voltmeters are not altogether suitable for ordinary work, but they are excellent laboratory instruments. Ordinary voltmeters have a range limited to a few hundred volts, but in many cases pressures are employed which run into thousands of volts. These high potential differences are frequently alternating, thus excluding at once a large number of measuring instruments; and it will readily be conceived that even those which we have described as capable of measuring alternating potential differences could not well be modified so as to measure up to 10,000 or even 2000 volts. A voltmeter was designed by Lord Kelvin, based upon the well-known elementary fact that two adjacent bodies at different potentials mutually attract each other. We have seen that a simple way of establishing this difference of potential is to rub two dissimilar substances, such as a piece of flannel and a piece of sealing-wax, together; they will then mutually attract each other, and the force of this attraction might serve to estimate the potential difference between them. Now, there is a difference of potential between the two poles of a battery, and if these two poles are connected one to each of two insulated metal conductors (say, brass spheres), the spheres will be at different potentials and will attract each other; this force of attraction is, however, too feeble to cause any perceptible movement, unless very delicate refinements, unsuitable for workshop use, are resorted to. But for this latter fact, such a method of measuring potential difference would be perfect in one respect, for, as the two conductors are insulated, so that no current whatever would flow from the battery, we might measure the potential difference without in the slightest degree altering it during the act of measurement. The use of this 'electrostatic' method, however,

becomes practicable in the case of high voltages, and fig. 124 shows one form of Lord Kelvin's voltmeter which is based upon it.

One conductor is fixed and the other movable; the fixed one consists of two butterfly-shaped sheets of brass, parallel to each other, and metallically connected, but carefully insulated from the

FIG. 124



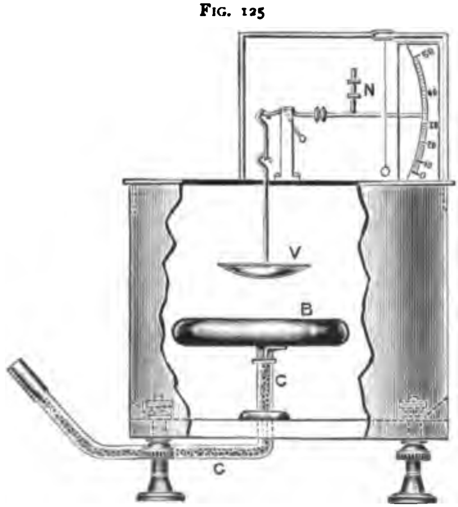
rest of the instrument. The movable conductor is a thin aluminium strip, supported at its centre on a knife-edge, and moving freely in a vertical plane exactly midway between the two fixed brass plates. When at rest the movable plate or strip is kept in a vertical position by very small weights placed on a knife-edge at

its lower extremity. If a difference of potential is established between the fixed plates and the movable strip, mutual attraction results, and the latter tends to set itself in a position as far as possible inside the fixed plates, this tendency being counteracted by the weights which it carries. The force of attraction is proportional to the square of the potential difference. The movable conductor, of course, comes to rest when the forces due to the electrostatic attraction and to gravity balance one another, and this position of rest is indicated by a light pointer moving over a graduated scale. This scale has 60 divisions, which represent equal differences of potential, and a large range is obtained by varying the balancing weights, three weights being supplied with every instrument. The actual value in volts of the potential difference competent to move the pointer through one division will, of course, depend upon the weight suspended at the lower part of the movable plate. With the particular instrument illustrated one division corresponds to 50 volts when the lightest weight is employed; twice the potential difference is required to produce the same effect when the next weight is added, or one division then represents 100 volts; while, when all the three weights are employed, one division corresponds to 200 volts, so that the maximum potential difference indicated by this particular instrument is $200 \times 60 = 12{,}000$ volts. The instrument is, however, made in three ranges with maxima of 8000, 12,000 and 20,000 volts respectively.

The case enclosing the conductors is of metal with a glass front, and the movable conductor is electrically connected by means of the knife-edges to this metallic case, which is provided with a suitable terminal screw. The knife-edges afford a sufficiently good connection in this instance, since they are not required to carry a current. The fixed brass plates are connected to a second terminal, which is carefully insulated from the case. The whole instrument is effectively insulated from earth by means of the stand upon which it is placed, and in order to measure the potential difference between two conductors it is only necessary to connect one conductor to one terminal and the other conductor to the other terminal and observe the reading of the pointer, with the appropriate weights on the bottom of the 'needle.' It is almost

unnecessary to add that too much care cannot be exercised in the measurement of high potential differences, and as a matter of fact no one should attempt any such measurements except after a considerable amount of experience under the direction of a qualified instructor, who must, of course, himself be an expert at the work. Where the apparatus is permanently fixed for constant use it may be protected by an insulating cover with a glass front; but it is during the making of changes, or during experimental work, that an accident is likely to occur. In some instances one of the two conductors between which a potential difference is to be measured is connected to earth, and this conductor should invariably be joined to the 'needle' and metallic case, and then should the case be touched by the experimenter he would experience no shock, because both the case and his body are earth-connected, and are therefore at the same potential. No part of the instrument, however, should be so touched while any 'live' conductor is connected to it, as such an action partakes of the nature of a test for the efficiency of the earth connection, which *might* be defective, and it also begets carelessness when using the apparatus under other conditions.

FIG. 125



In a modified form of this instrument much higher ranges are attained. The instrument is called the volt balance and is made in two sizes, one ranging from 5000 to 30,000 volts and the other from 5000 to 100,000 volts. The principle upon which the instrument is constructed is illustrated in diagrammatic form

in fig. 125. It consists of a fixed and highly insulated metal plate, B, supported by a large porcelain insulator, C, which projects below the base of the instrument, and through which the high-pressure connection is made. Above this plate is fitted a light aluminium pan, V, which is attached to a movable link system so that the pan can be attracted in proportion to the voltage and cause a pointer, which is shown above the earth-connected case of the instrument, to travel over a vertical scale. With the higher range instrument two weights are provided, one indicating from 5000 to 30,000 volts and the other from 20,000 to 100,000 volts. The pointer is, in the diagram, shown to be carrying weights at N, against which the force of attraction between B and V has to act. The instrument is very compact, and every possible precaution has been adopted to avoid any risk of danger in handling it, but of course the personal equation is a factor that must not be overlooked, and, as we have already indicated, the measurement of potentials of such high values should only be attempted by those who have a knowledge of the risks involved. The instrument of the lower range is made in a portable form and is more particularly adaptable for the practical testing of the insulation of cables. It is therefore fitted in an insulating case, and is provided with a wood box supported on porcelain insulators so that the instrument can be used inside the box.

For accurately measuring lower potential differences the instrument cannot be made in such a simple form, as with only one movable metallic strip it would be difficult to obtain a sufficiently great force of attraction. The requisite attractive force can, however, be obtained by employing a greater number of 'needles' or vanes, each moving between a pair of fixed conductors, and such an instrument is called a 'multicellular' electrostatic voltmeter. Fig. 126 illustrates such a voltmeter, the working parts being shown separately in fig. 127. The instrument is made in several ranges, the lowest being from 10 to 80 volts with one volt divisions. The instrument illustrated has ten aluminium vanes, V, which are arranged horizontally and equidistant from one another. They are fixed on a vertical spindle and are all in metallic connection. This spindle is supported by a platinum-iridium wire, W, which is set so that the pointer, which is rigidly

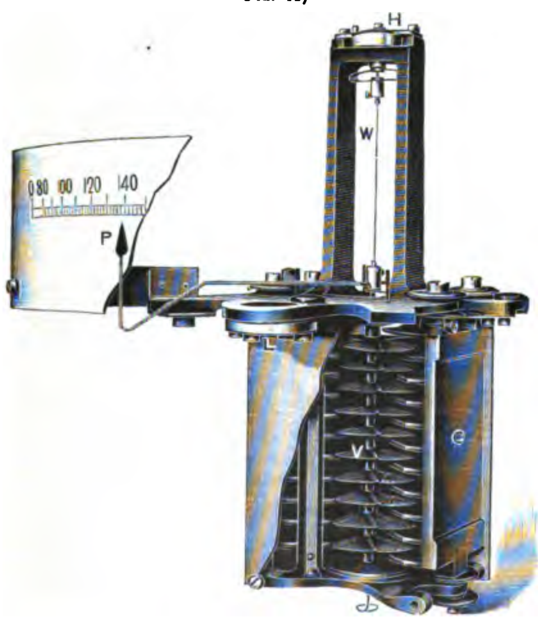
attached to the spindle, stands at zero when no electrical difference exists between the vanes and the rest of the instrument. The free end of the pointer passes over a scale calibrated to read directly in volts, a mirror being placed under a slot in the scale (fig. 126), in order that errors due to parallax may be avoided. It will be noticed that in fig. 126 the scale is horizontal, while

FIG. 126

in fig. 127 it is vertical, the pointer P in this case being bent up at right angles, so that the indications can be easily read at a distance. The lower end of the spindle carrying the vanes dips into a dash-pot, which protrudes below the case of the instrument, but which is not shown in either of the figures. The object of the dash-pot is to steady the movements of the pointer and to render it practically dead-beat. The pointer is electrically connected with

the case of the instrument, the movable parts of which are effectively screened so as to render the case absolutely neutral and allow it to be connected to earth with perfect safety. The fixed conductors between which the aluminium vanes play are horizontal brass plates fixed into vertical brass plates, C, all connected together, but insulated from the outer brass case of the instrument; they constitute, in fact, a series of 'cells,' whence the name of the

FIG. 127



instrument. Only one set of vanes and cells is distinctly visible in the figure, but there is a corresponding set of vanes on the opposite side of the spindle, lying further back in the case. The fixed plates are connected to one of the insulated terminals, T T (fig. 126), and the spindle carrying the movable vanes is connected to the other terminal through the medium of the liquid in the dash-pot, instead of through the suspension as was formerly done.

This has the advantage of preventing any damage to the moving system by accidental contact of the vanes with the cells, as the liquid in the dash-pot has a high resistance and prevents, therefore, the flow of a heavy current.

When a difference of potential is set up between the fixed and movable conductors, the attractive force urges the latter to take up a position inside the former, thus giving a rotary motion to the vertical spindle. The torsion thus put on the suspending wire, which terminates in the torsion head H (fig. 127), works against this force, and the position at which the two forces balance, as indicated by the pointer, shows the potential difference. Suitable guiding holes, through which the spindle passes, and vertical brass plates limit the movements of the spindle and prevent contact between the two sets of conductors under ordinary circumstances. Levelling screws, S S (fig. 126), are provided, which, by the aid of the spirit level L (figs. 126 and 127), can be used for ensuring the proper relative positions of the vanes and cells. The particular form of instrument illustrated is obviously a portable one, and a packing screw B (fig. 126) is provided, which, when unscrewed, lifts the suspension and secures the movable vanes, thereby preventing any injury to the suspension when the instrument is moved from place to place.

Since an electrostatic voltmeter allows no current to pass between the two points whose potential difference it indicates, there is, as we have said, no possible chance of any error similar to that due to the heating of the coils in an electro-magnetic voltmeter. Further, there is no waste of energy as in the latter case, and an electrostatic instrument may therefore be kept permanently connected between the two mains of an electric-light circuit without adding to the coal bill.

Another important feature common to instruments of this type is that they may be used to measure either steady or alternating potential differences with equal facility. In an electro-magnetic voltmeter the indications of the needle are dependent upon the strength of the current flowing through the coil, which should vary exactly with the pressure between the ends of the coil; and with a steady uni-directional pressure this proportional variation does take place, because the resistance of the coil (supposing the

heating effect to be negligible) remains constant. But with an alternating potential difference the value of the resulting alternating current depends upon the 'self-induction' as well as the resistance of the coil, and the effect of the self-induction changes with the rate at which the current alternates. Consequently, although an electro-magnetic voltmeter may be calibrated to indicate correctly for a certain rate of alternation, it will not necessarily be correct for any other rate. An electrostatic instrument, being quite free from any self-induction effect, is independent of the rate of alternation. Moreover, since the instrument is calibrated to read in volts, while the force of attraction between the plates varies as the square of the potential difference, it indicates directly the value of the square root of the mean square of the potential difference between the plates, which, as the student will presently learn, is the value generally required to be known.

There are other forms of electrostatic voltmeters, all of which are, however, similar in principle to those described, and no difficulty should be experienced in understanding their construction and action. In some cases a small mirror is attached to the movable conductor, and the mirror reflects a luminous beam on to a scale placed in front of it. The movements of the spot of light indicate the deflections of the needle, and therefore also the potential difference which causes those movements.

CHAPTER VII

ELECTRO-MAGNETS—ELECTRO-MAGNETIC INDUCTION

IT has been observed that the air space in the neighbourhood of a wire, in which the effect of a current travelling in the wire is perceptible, is called an electro-magnetic field, and that the direction in which the force in this field acts can be made evident by means of iron filings, which, if sprinkled upon a sheet of paper with the wire passing through it, arrange themselves in concentric circles along the lines of force round the wire. And further, it will be remembered that some substances offer greater facilities than others for the propagation of these lines of force; and that it is possible to alter their circular form by bringing near them some substance through which they pass with either more or less ease than through the air. The relative capability possessed by any substance for conducting these lines of force is known as its 'permeability,' and it is obviously desirable that some method of definitely comparing this property in various bodies should be adopted. The permeability of air can be taken as the standard, and the permeability of all other substances measured by comparison with it. As a matter of fact, the permeability of a vacuum is taken as unity; but that of air is almost exactly the same, and is a more convenient standard.[1]

[1] There is another way of looking at this phenomenon. It is an old idea which has been revived in recent years, and the student may in some cases find it an easier one in comprehending the effect of placing a magnetic substance in a magnetic field. The assumption is that in a magnetic substance every molecule is in itself a permanent magnet. In the unmagnetised state the molecules are supposed to be so arranged that they neutralise the magnetic effect of one another. When brought within the influence of a magnetic field, however, they rearrange themselves with their axes more or less in the direction of that field, and the substance is then said to be magnetised. The resultant field results from the superposition of the lines

If a piece of hard steel is placed in any magnetic field, many of the adjacent lines of force are bent out of their previous shape, and converge into the steel. More lines of force, therefore, pass through the space occupied by the steel than pass through that same space when occupied by air alone. Hence we conclude that the lines of force pass through steel more readily than through air, or the permeability of steel is greater than that of air. If, again, the steel is replaced by a piece of soft iron of similar shape and size, even more lines of force will now pass through the same space, showing that the permeability of soft iron is still greater than that of steel. In fact, the permeability of any substance might be estimated by dividing the number of lines of force which thus pass through it by the number which pass through the same space when the substance is removed, the strength of the magnetising field being the same in both cases. There is, however, no method available for determining the actual number of lines of force pervading any particular space or substance. The nearest approach to such a desideratum would be to measure the relative strength of any electro-magnetic field, or of any given portion of it, because, as might be supposed, the strength of the field varies directly as the number of lines of force pervading it. It is possible to compare the strength of fields by measuring the magnitude of various phenomena which can be made to take place in them, and one such method is described at the end of this chapter.

We can by such means measure the strength of a field due to any magnetising force—that is to say, we can obtain certain effects proportional to the number of lines of force passing

of force, due to the rearranged magnets, on the original field, and thus the distortion of the lines of force is produced. When all the constituent particles have been rearranged, the substance is said to have become 'saturated.' Some substances require the action of a stronger magnetic field to rearrange their constituent particles than others; thus for a given magnetic force (within the limits of saturation) hard steel will not become so strongly magnetised as soft iron, and on that account soft iron is said to have a higher 'permeability' than hard steel. Both methods of viewing the question of permeability or magnetic conductance, as it may be called, lead us to the same end, viz. that a magnetic substance is magnetised when it is placed in a magnetic field; and as the method adopted in these pages is generally the simpler, and perhaps more instructive, we can scarcely do better than adhere to it.

through any given air space—and then, filling that same space with a piece of iron, ascertain the relative number then passing through the iron. The number of lines of force passing through an area of one square centimetre taken at right angles to the lines is called the 'magnetic induction,' this term being employed as an abbreviation of 'intensity of magnetic induction'; the magnetic induction through the air space is equal to the strength of the magnetising field (since the permeability of air is 1), and the magnetic induction through the iron, divided by the strength of the magnetising field, gives the permeability of the iron.

By experimenting in this way it has been proved beyond doubt that not only do different substances possess various degrees of permeability, but also that this property may vary considerably in the same substance under varying conditions; and it is also possible to arrange the various substances in the order of their relative degrees of permeability. The most permeable material known is pure soft iron, and it is found that, generally speaking, as the hardness and impurity of the iron increase, so its permeability decreases; that of hard steel, cobalt, and nickel, and especially of a certain kind of manganese steel, being comparatively low. The vast majority of substances, including most of the metals other than iron or steel, are to all intents and purposes equal to air in this respect, while the permeability of a few metals, including bismuth and copper, is very slightly less than that of air. To take the two extreme cases, the permeability of iron has been known to exceed 2000—that is to say, more than 2000 times as many lines of force have been known to pass through a certain piece of iron as passed through the equivalent air space when the iron was absent—while that of bismuth has been found to be not much below 0·9999.

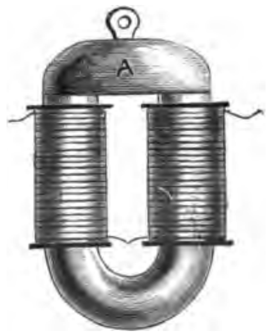
This property is very important in some practical operations, and (especially in the case of iron) it is useful to know the conditions under which it varies in the same material. We have already touched upon a practical application in the case of a helix or solenoid, and are now in a position further to consider the matter. We observed that the electro-magnetic effect of a helix of wire carrying a current can be increased in two ways—either by increasing the strength of the current and so increasing the actual

number of lines of force produced, whatever that number may be, or by increasing the effect of the available lines of force by making as many of them as possible pass through that space near the ends where they will be able to act to the greatest advantage. The permeability of bismuth and copper being less than that of air, either of these substances, when placed in an electro-magnetic field, will *decrease* the number of lines of force passing through the space which it occupies ; but even in the case of the most effective substance known, viz. bismuth, the difference is so very slight that it is difficult to perceive or measure it. If, however, any substance were to be discovered with a permeability very much less than that of air, one way of leading the lines of force through the desired space would be to place this substance of low permeability in that part of the field from which it is wished to exclude those lines—that is to say, to make all paths but the right one, or the one desired, as difficult as possible. But the permeability even of bismuth being so little inferior to that of air, the only available method of attaining the desired end is to make the path which it is desired the lines of force should take as easy as possible. In the case of the solenoid described in Chapter IV. we wished to increase its effect by leading as many as possible of the lines of force through the ends of the coil, instead of allowing them to leak out at the sides, and for this purpose fitted it with a soft-iron core, which had the desired effect. Since the permeability of different qualities of iron varies so much, too great care cannot be exercised in its selection ; and, experiment having shown that soft annealed Swedish iron is superior to all other kinds, this should, when the question of expense does not forbid, be used in all cases where it is desired to concentrate the lines of force at any particular point. The best Swedish iron is, however, somewhat difficult to obtain, and the same remark applies to the very best Yorkshire brands (Bowling, Lowmoor, &c.), which are scarcely inferior to Swedish iron. Although for some small machines and instruments it is imperative to employ the best iron procurable, yet for heavier machines it is frequently cheaper to employ a slightly inferior iron, and use a greater quantity of it, and consequently of wire also, to obtain the desired result. As a matter of fact there is now obtainable in any desired quantity a class of steel which possesses

most of the magnetic qualities of good soft iron. This matter is referred to later on.

It will be remembered that a helix of wire fitted with an iron core is called an electro-magnet, and electro-magnets differ in shape and arrangement according to the work they are intended to perform. Thus if it were wished with one pole of an electro-magnet to repel a similar pole of another electro-magnet, or of a permanent steel magnet, with as much force as possible, it should be made long and straight, so that its opposite pole might be as far away as practicable. It frequently happens, however, that an electro-magnet is required either to support a heavy weight or to attract another magnet or a piece of iron as powerfully as possible. It is then more advantageous to allow both poles of the electro-magnet to act together, and this can be accomplished by making it in what is called the horseshoe shape, bringing the poles close together, as illustrated in fig. 128. In such cases the wire is wound over only the 'legs' of the iron core.

FIG. 128



In designing an electro-magnet, therefore, the object to which it is intended to apply the apparatus must be kept clearly in view, and it is necessary that the general principles underlying electro-magnetic construction should be now considered, although, under the most favourable circumstances, these laws and principles are somewhat complicated and involved, and, to a great extent, indeterminate.

In the generation of an electro-magnetic field by means of a solenoid there are two prime features to be taken into consideration, viz. the strength of the current and the number of convolutions of wire constituting the coil. It can readily be understood that the electro-magnetic effect produced by a current varies directly as the strength of that current, so that to double the intensity of the field developed by any particular coil it will suffice to double the current strength. There is, in such circum-

stances, no need to take into account the resistance of the wire, except in so far as it may, by being heated by the current, modify the current strength, the resistance varying, in the ordinary course, directly as the length, and inversely as the square of the diameter, of the wire.

As the current strength in any circuit is the same in all parts, or at all points, of that circuit, the electro-magnetic field developed by any one length—say one inch of the wire—is exactly equal to that developed by any other portion of the circuit of equal length. It follows, therefore, that two convolutions or turns of wire close together will generate a field twice as strong as that which can be developed by either of the turns taken separately; and, speaking generally, it can be said that the field developed by a solenoid carrying a given current varies in strength directly as the number of convolutions, and this will be true whatever the nature of the material forming the conductor, or whatever its resistance.

In order to arrive at a more precise understanding, let us again consider the problem set us, supposing we desire to make an electro-magnet similar to that illustrated in fig. 128 as effective as possible. The object is to attract the 'armature' A, with the maximum force, and in order to attain this result we want to urge as many lines of force as we possibly can through that armature.

Now, when we wish to calculate the strength of a current of electricity which will be obtained in any given electrical circuit under certain conditions, we take into account the electro-motive force which urges the current through the circuit, and the resistance against which that electro-motive force has to act, the resulting current being directly proportional to the former and inversely proportional to the latter, and we write

$$\text{Current strength} = \frac{\text{Electro-motive force}}{\text{Resistance}}.$$

Somewhat similarly we may consider the whole path round which we desire to urge magnetic lines of force as a magnetic circuit, and take account of the total magnetising force which tends to urge the lines of force round the circuit as well as the 'magnetic

resistance' against which that force must act in order to produce the result. Then we may say

$$\text{Total number of lines of force} = \frac{\text{Magneto-motive force}}{\text{Magnetic resistance}},$$

where the term magneto-motive force represents the total magnetising force acting round the whole circuit. This magneto-motive force is for any magnetic circuit *proportional* to the current strength and to the number of convolutions in the solenoid—that is to say, to the 'ampere-turns'—as was mentioned above in the general view of the case. There is one point here however, which is worthy of notice. When we speak of the electrical resistance of a conductor we associate with that resistance the idea of work having to be performed in urging a current against it. When, however, we are dealing with magnetic resistance the case is different, as no corresponding expenditure of energy is involved, and in these circumstances the property of resisting, or, rather, of not allowing, magnetic lines of force to pass through freely, is called *reluctance*. Magnetic resistance or reluctance does not therefore involve an expenditure of energy or the corresponding generation of heat in urging a magnetic flux or a series of lines of force against it. A certain small amount of heat is produced as a consequence of the alteration in the arrangement of the molecules of iron, but this heat bears but little relation to the resistance or reluctance of the metal, and may be more rightly regarded as a consequence of its retentivity.

In order to adapt all results to the C.G.S. system of measurement we unfortunately require to introduce other factors. In the first place the C.G.S. unit of current is equal to 10 amperes, so that, the C.G.S. unit of current being adopted in the fundamental calculations, the ampere-turns must be divided by 10; and, then, for reasons which cannot be stated simply, we must multiply the ampere-turns by 4π. If, therefore, we denote the strength of the current as measured in amperes by C, and the total number of convolutions by N, the magneto-motive force will be equal to

$$\frac{4\pi \times C \times N}{10}, \text{ or } 1{\cdot}2566 \times C \times N.$$

We must now consider the question of the magnetic resistance offered to this magneto-motive force, and here again an analogy with the electrical circuit may help us, although the two cases are not strictly analogous. The resistance of a simple electrical circuit varies directly as the length of the circuit, l, inversely as the sectional area of the conductor, a, and inversely also as the specific conductivity of the conductor, m, specific conductivity being the inverse of specific resistance. This may be stated as

$$\text{Resistance} = \frac{l}{a \times m}.$$

In a magnetic circuit permeability, or the relative capability of conducting lines of force, is analogous to electrical specific conductivity; and the magnetic resistance, like electrical resistance, is directly proportional to the length of the circuit, l, and inversely proportional to the sectional area, a.

Consequently,

$$\text{Magnetic resistance} = \frac{l}{a \times \mu},$$

l being preferably measured in centimetres, a in square centimetres, and μ standing for the permeability of the substance of which the magnetic circuit is composed.

In order, therefore, to calculate the number of lines of force flowing round any circuit, which number we may conveniently denote by **N**, we may say

$$\mathbf{N} = \frac{\text{Magneto-motive force}}{\text{Magnetic resistance}},$$

that is,

$$\mathbf{N} = \frac{\dfrac{4\pi \times \mathrm{C} \times \mathrm{N}}{10}}{\dfrac{l}{a \times \mu}}$$

or

$$\mathbf{N} = \frac{1 \cdot 2566 \times \mathrm{C} \times \mathrm{N} \times a \times \mu}{l},$$

where C represents the current strength in amperes, and N the total number of convolutions in the solenoid. The total number

of lines of force, N, is frequently referred to as the 'magnetic flux,' or simply the 'flux'; and the term 'reluctance' is, as we have said, frequently applied to the magnetic resistance of any magnetic circuit or part of a circuit.

The matter may, perhaps, be rendered clearer by assuming a set of conditions for the electro-magnet depicted in fig. 128. Suppose the number of convolutions on each limb to be 200; then $n = 2 \times 200 = 400$; also that the current strength is 80 milliamperes or ·08 ampere. Let the mean length of the magnetic circuit (that is, the length measured round the circuit through the middle of the core and armature) be $l = 12$ centimetres, and the area of the core and armature at any point be $a = 3$ square centimetres. The permeability of the iron will vary with the number of lines of force which pass through it, but we will assume it to be $\mu = 500$.

Then in this case

$$N = \frac{1·2566 \times ·08 \times 400 \times 3 \times 500}{12} = 5026;$$

that is to say, if we could at any point cut the magnetic circuit without disturbing the arrangement, we should find 5026 lines of force passing across between the two faces of iron so separated.

Unfortunately, we do not find the problem quite so easy in actual practice. We have here ignored the fact that some of the lines of force would leak out from the iron, and not pass completely round the desired path. Further, although the armature and pole-faces may be accurately faced up and fit truly, the two joints in the magnetic circuit will make the reluctance appreciably higher than it would be were the fibre of the iron continuous throughout.

Were the armature to be separated from and fixed at a little distance (say 1 centimetre) from the pole-faces, a great increase in the reluctance would take place, causing a corresponding reduction in the number of lines of force passing through the armature, and hence a diminished force of attraction. The reluctance of each air-gap would be $\frac{l}{a \times \mu} = \frac{1}{3 \times 1} = \frac{1}{3}$, the value of μ being 1 for air, so that for the two air-gaps $\frac{2}{3}$ would have to be

added to the reluctance of the magnetic circuit. In addition to this, the leakage would be greatly increased, many of the lines of force passing across the air space between the two magnet limbs instead of through the armature, and this also would have to be allowed for, as will be presently shown.

It is frequently convenient to speak of the intensity of the magnetising force at any point, instead of the magneto-motive force or total magnetising force, and the value of this intensity at a point is denoted by the symbol **H**. It is measured by the force in dynes with which a magnet-pole of unit strength would be acted on at the point in question, and obviously may vary considerably at different points round a complex magnetic circuit. If we consider the case of a long straight evenly wound solenoid, the value of **H** will be practically uniform inside it along its whole length except just at the ends, and it will evidently vary with the density of the convolutions of wire, or the number per unit of length of the solenoid. The value of **H** will in fact be $\frac{4\pi C \times n}{10}$ dynes, where C is the current strength in amperes, and n the number of convolutions per unit of length of the solenoid. Thus, if with the same length of wire the solenoid were uniformly stretched or re-wound so as to become double its original length, the total number of turns remaining the same, the value of **H** at any point would be halved, because the number of convolutions per unit of length would be halved. But since the total number of convolutions, N, is unaltered, the value of the magneto-motive force is the same as before. Now, it can be proved that for a very long solenoid of length l centimetres the value of the magneto-motive force is equal to $\mathbf{H} \times l$; or, the magnetic force at a point **H** may be found by dividing the magneto-motive force (that is, the total magnetising force) by l, the length of the solenoid. The case is rendered clearer and more exact if we take a solenoid wound uniformly over a non-magnetic tubular ring. If the solenoid had n convolutions per centimetre, and the mean circumference of the ring were l centimetres, then a unit magnet-pole would experience a force of $\mathbf{H} = \frac{4\pi C n}{10}$ dynes at any point in the interior of the solenoid, and it would require the expenditure of **H** ergs of energy to

move it through a distance of one centimetre against the magnetising force, and therefore $\mathbf{H} \times l$ ergs to move it all the way round the solenoid, $\mathbf{H} \times l$ being thus a measure of the magneto-motive force. Let the diameter of the ring be now increased sufficiently to double its mean circumference; then the convolutions will be half as dense as before, being only $\frac{n}{2}$ per centimetre, and consequently the value of $\mathbf{H}$ will be halved. But the distance through which the magnet-pole must be moved to make the complete journey has been doubled, and therefore the total expenditure of energy is still $\frac{\mathbf{H}}{2} \times 2\,l = \mathbf{H} \times l$ ergs, proving the magneto-motive force to be the same as before.

It is also sometimes necessary to specify the density of the lines of force at any given point, or the number passing through a square centimetre whose plane is at right angles to the direction of the lines, and this density is denoted by the symbol $\mathbf{B}$. If the magnetic circuit be not perfectly uniform throughout, the value of $\mathbf{B}$ may differ considerably at different parts thereof. Thus, supposing the armature to be entirely removed from the electromagnet shown in fig. 128, most of the lines of force would pass as far as possible through the iron core, and would be approximately equally dense at all parts thereof except near the poles. Here they would begin to leak out at the sides of the iron core instead of all passing out through the ends or pole-faces, and in crossing from one pole to the other through the air space they would spread out in all directions. The value of $\mathbf{B}$, then, would be rather less in the iron near the pole-faces than at the bend and inside the solenoids, while it would be comparatively small in the air space.

If we wound an iron ring uniformly with wire, through which a current was made to flow, practically all of the lines of force would make the complete circuit through the continuous iron ring and the value of $\mathbf{B}$ would be the same at all parts thereof. Suppose the area of cross-section of the iron to be 3 square centimetres, and the total number of lines of force $\mathbf{N}$ to be 27,000, then the value of $\mathbf{B}$ at any point would be $\frac{\mathbf{N}}{3} = 9000$. If the

iron core were removed, we may suppose the value of B to fall to 15, that is, 15 lines of force per square centimetre, and we thus obtain a measure of the increase in the number of lines of force due to the presence of the iron core, which, as we know, measures the 'permeability' of the iron. If the interior of the solenoid is occupied by air or any other non-magnetic substance, a magnetising force of value H can produce H lines of force per square centimetre, and H is in air equal to B. By the addition of an iron core B increases but H remains unaltered, and the permeability of the iron is

$$\mu = \frac{B}{H}.$$

In the instance just mentioned, then, the permeability of the iron would be $\frac{9000}{15} = 600$ under the existing conditions.

The best way of ascertaining the manner in which the value of B and μ vary in any given sample of iron or steel for different values of the magnetising force H, is to determine experimentally the value of B for a number of values of H from zero upwards, and the results are conveniently shown by plotting curves. This subject will be referred to at the close of this chapter.

It will be observed that by simply increasing the diameter of an iron core, and also the diameter of the convolutions of the helix surrounding it, we do not alter the value of H or B provided the current strength remains constant, because, although we thereby increase N, the total number of lines of force, the corresponding increase in the area of the core leaves the density the same as before.

It must be remembered, however, that supposing the electromotive force available to be a fixed quantity, any increase or decrease in the diameter of the coil must, if the number of convolutions is to remain constant, proportionally increase or decrease the length of wire and its resistance, and cause thereby a decrease or increase in the current strength, unless this variation in the length of the wire is accompanied by a corresponding variation in its cross-section, so as to keep the resistance constant.

Again, supposing the dimensions of the core be kept constant,

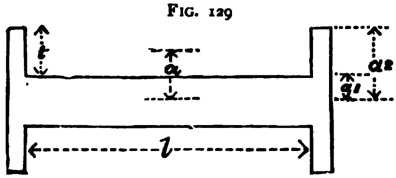
and that it is desired to magnetise it more strongly by adding to the number of convolutions, care must be taken that in this instance also the current strength is kept constant by a corresponding increase in the potential difference at the ends of the coil. Were the potential difference to remain unaltered, the additional convolutions would not bring about any increased magnetisation of the core. For example, if the number of convolutions were doubled, the resistance of the coil would be at least doubled, and the current therein halved, so that the ampere turns would remain unaltered.

If a coil consists of a number of layers, it must be remembered that the length of the wire in the outer layers will be appreciably greater than in the inner. To take an extreme case, we will suppose the coil to consist of ninety-nine layers, in which case the length of wire composing the ninety-ninth layer would be considerably greater than that forming the first. Now, the circumference of a circle varies directly as its diameter, and is equal to $2 \pi r$, where π is the ratio between the circumference of a circle and its diameter (or 3·1416), and r is the radius of the circle. If, therefore, the diameter of the outside layer is actually twice that of the inside, the length of the wire in each of the larger turns, and consequently in the whole layer, will be exactly doubled, and its resistance doubled also; and the intermediate layers will vary proportionately. But the actual resistance of the whole coil can be easily calculated, for if the radius of the inside layer, the resistance of which is, say, 5 ohms, is half an inch, and that of the outside layer one inch, the mean or average radius will be three-quarters of an inch—that is to say, the length of wire in the fiftieth layer will be half as long again as that in the first. Its resistance will therefore be 7·5 ohms. Similarly, the resistance of the first and last layers together will be 15 ohms, or an average of 7·5 ohms per layer, and this will be true of every similarly situated pair of layers, so that the total resistance of a number of layers is equal to the resistance of the middle or average layer multiplied by the number of layers. In the coil under consideration the resistance will be

$$R = 7 \cdot 5 \times 99 = 742 \cdot 5^{\omega}.$$

When the field due to a certain coil, consisting of many layers, is insufficient for a given purpose, it may become advantageous to re-wind the bobbin with wire of a smaller gauge, so as to get a greater number of turns into the small compass. A reference to the diagram, fig. 129, will simplify some of the difficulties involved in a consideration of this matter. Let us suppose the figure to represent a wooden or ebonite bobbin, and that the length, l, of the space occupied by the coil, or the distance between the 'cheeks' of the bobbin, is 3 inches, while the radius, a_1, of the bottom layer to be wound is a quarter an inch, and the extreme radius, a_2, of the coil three-quarters of an inch. The mean radius, a, will be half an inch, or

FIG. 129



$$a = \frac{a_1 + a_2}{2} = \cdot 5.$$

The total thickness, t, of the coil or of the layers will also be half an inch, or

$$t = a_2 - a_1 = \cdot 5.$$

As we have already seen, the length of one turn of wire of radius a_1 will be $2 \pi a_1$ and, if there are n turns in that layer, the length of wire comprised in it will be $2 \pi a_1 \times n$. Supposing there to be m layers in the coil, having the mean radius a, the total length L will be

$$\text{L} = 2 \pi a \times n \times m \quad . \quad . \quad . \quad . \quad . \quad (1).$$

Now, as, in winding a number of layers of wire in a coil, each turn must somewhere or other *cross* the subjacent turn, it follows that the turns of any one layer cannot be placed evenly in the grooves or recesses between the turns of the layer immediately underneath it; or, in other words, if we assume the wire, with its insulating covering, to have a diameter, d, the section of the space occupied or appropriated by that wire will really be a

square whose side is equal to d. Consequently, in one layer the number of turns n will be

$$n = \frac{l}{d},$$

and the number of layers, m, will be

$$m = \frac{t}{d}.$$

Substituting these values for m and n in (1) we get

$$\text{L} = 2\,\pi\,a \times \frac{l}{d} \times \frac{t}{d} = \frac{2\,\pi\,a \times l \times t}{d^2} \quad . \quad . \quad . \quad (2).$$

For example, let the diameter of the wire, with its insulating coating, be 50 mils (the mil is the thousandth part of an inch), then the length of this wire that would be required to fill the bobbin illustrated in fig. 129 would be

$$\text{L} = \frac{2\,(3{\cdot}1416) \times 0{\cdot}5 \times 3 \times 0{\cdot}5}{(0{\cdot}05)^2} = 1885 \text{ inches} = 52\tfrac{1}{3} \text{ yards}.$$

We are thus able to calculate not only the length of wire required to fill any bobbin, but also its resistance, the resistance per unit of length being ascertainable from tables. Moreover, the total number of turns of wire can be easily calculated, for, m being the number of layers and n the number of turns in each layer, the product $m\,n$ will give the total required, but

$$m = \frac{t}{d}, \text{ and } n = \frac{l}{d};$$

$$\therefore\; m\,n = \frac{t\,l}{d^2},$$

$$\text{or } m\,n = \frac{0{\cdot}5 \times 3}{(0{\cdot}05)^2} = 600 \text{ turns}.$$

Let it now be supposed that a given bobbin—say of the dimensions shown in fig. 129—is to be filled with copper wire which shall offer a definite resistance, say 5 ohms. There are then only three quantities known, viz. the dimensions of the bobbin, the resistance which the coil is to offer, and the specific

resistance of the copper; while the length of the wire and its diameter are unknown and require to be ascertained. The space in which the wire is to be wound can be calculated from the given dimensions, for, V being this space or volume,

$$\text{V} = \pi\, l\,(a_2{}^2 - a_1{}^2) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1).$$
$$\text{or V} = 3{\cdot}1416 \times 3\,(0{\cdot}75^2 - 0{\cdot}25^2)$$
$$= 4{\cdot}712 \text{ cubic inches.}$$

But supposing, as will be actually the case, that the wire, whose diameter is d, occupies the same space that it would take were it to be square instead of round, then, manifestly,

$$\text{V} = \text{L} \times d^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2).$$

As, also, the total resistance of the wire varies directly as its length, directly as its specific resistance s (which, in this case, as the other dimensions are in inches, we take as the resistance between opposite faces of an inch cube), and inversely as the area or cross-section of the wire,

$$\text{R} = \frac{\text{L} \times s}{area}.$$

But the area of the insulated wire is equal to $\pi\, r^2$, or $\pi \left(\frac{d}{2}\right)^2$, that is, $\pi \frac{d^2}{4}$.

Therefore
$$\text{R} = \frac{\text{L} \times s}{\pi \frac{d^2}{4}},$$

that is,
$$\text{R}\,\pi \frac{d^2}{4} = \text{L}\, s,$$

or,
$$\text{R}\,\pi\, d^2 = 4\,\text{L}\, s,$$

and
$$d^2 = \frac{4\,\text{L}\, s}{\text{R}\,\pi} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3).$$

But from (2) it will also be seen that

$$d^2 = \frac{\text{V}}{\text{L}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4).$$

Consequently $$\frac{4 \text{ L } s}{\text{R } \pi} = \frac{\text{V}}{\text{L}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5),$$

and $$4 \text{ L}^2 s = \pi \text{ R V}.$$

Therefore $$\text{L}^2 = \frac{\pi \text{ R V}}{4 s},$$

and, finally, $$\text{L} = \sqrt{\frac{\pi \text{ R V}}{4 s}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (6).$$

By inserting the numerical values on the right-hand side of this equation, the length L, having the required resistance, can therefore be found, after which we can, by equation (4), determine also the gauge of the wire. It must, however, be noted that, for simplicity, d is taken as the diameter of the bare wire in equation (2), thus rendering the result only approximate; but when the thickness of the wire is great as compared with that of the insulation, the formulæ approach very closely to the truth. A method of making these calculations, in which the space occupied by the insulating covering is allowed for, was fully explained by the authors in the 'Electrical Review' for June 5 and 12, 1896.

It is frequently useful to know the exact length of any particular wire which can be wound on any particular bobbin, and, knowing V and d, this can be easily ascertained, for if d_1 represents the outer diameter of the wire and its covering, V the volume of the wire space, and L the required length, then

$$\text{L} = \frac{\text{V}}{d_1{}^2}.$$

Returning now to the consideration of the core of an electromagnet, it is evident that, generally speaking, it is advantageous to make the magnetic resistance of the magnetic circuit as low as practicable, in order to obtain the requisite number of lines of force with the minimum magneto-motive force; and, consequently, the three factors, length, sectional area and permeability, should receive due consideration in determining the dimensions of the core and the material of which it is to be composed.

If, as is sometimes the case, lightness and compactness are important, it is essential to employ for the core annealed wrought iron of high permeability, as then the desired effect can be

obtained with the minimum sectional area. But should the question of weight be of secondary importance, iron of lower permeability—even cast iron—may be employed. For example, in the case of the massive cores for the field magnets of dynamo machines, the requisite quantity of the highest quality wrought iron is not only expensive as regards first cost, but it requires a further and considerable expenditure upon it in forging and machining it up to the proper shape and dimensions for fitting the parts together and in forming the cavity for the reception of the rotating armature. Cast iron is not only cheaper, but the material may be cast to such a shape that it requires but little further work to be done upon it; and by sufficiently increasing the sectional area of the core over and above that which would be required if it were made of wrought iron, the lower permeability is compensated for. It must not be forgotten, however, that such an increase in the sectional area of the core necessitates the employment of a correspondingly greater quantity of copper wire for the magnetising coil, for each convolution is, of course, increased in length, and in most cases the wire must also be increased in thickness to prevent the greater length increasing the resistance of the coil. Mild steel combines to a considerable extent the good features of wrought iron and cast iron for heavy electro-magnet cores, for it can be cast into moulds as readily as cast iron, while some qualities have a permeability not far short of that possessed by the best wrought iron. Such mild steel contains a very small percentage of carbon and cannot be hardened and tempered like tool-steel (which contains a much greater proportion of carbon, and has a correspondingly lower permeability). Mild steel, in fact, is, in its chemical composition, practically the same as wrought iron, although it is crystalline in its structure, on account of the fact that its particles settle down under no external restraining force when the metal solidifies from the molten state in which it is manufactured. This crystallinity can be somewhat reduced by hammering and rolling, and it is absent in good wrought iron which has been hammered and rolled while cooling from a high temperature, until it is fibrous throughout. Even wrought iron, if raised to a very high temperature and then allowed to cool in the absence of these mechanical restraining forces, becomes crystalline,

and loses to a great extent its valuable mechanical and magnetic qualities.

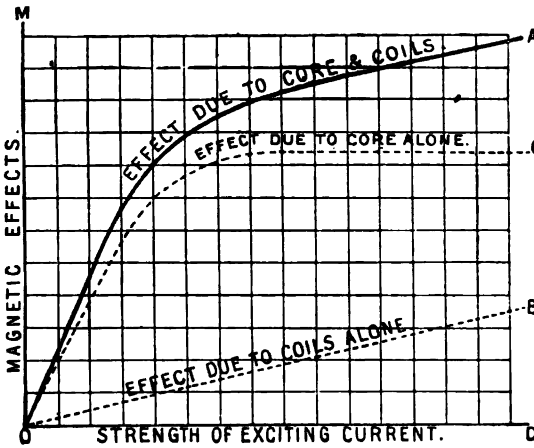
It is evident that before the dimensions of the core of an electro-magnet, such as that employed for a dynamo field-magnet, can be decided upon, it is necessary to know the permeability of the metal which is to be employed for the purpose; and since the permeability of iron or steel varies considerably with the density of the lines of force passing through it, that is to say, with the value of **B**, it is necessary to decide upon the maximum density at which the core is to be worked. If a piece of iron destitute of magnetisation be experimented upon, by observing the number of lines of force obtained through it with a number of gradually increasing values of magnetising force, it will be found that the effect of producing a *few* lines of force through the iron is to slightly raise the value of its permeability, but after a certain number of lines have been urged through the iron the permeability rapidly diminishes in value, and beyond a certain point a considerable increase in the magnetising force makes but little difference in the value of **B**. When it thus becomes very difficult to urge additional lines of force through a piece of iron, it is said to be magnetically 'saturated,' but no definite point has yet been reached at which it can be said to be absolutely impossible to increase the number. Professor Ewing has succeeded in forcing 45,350 lines of force per square centimetre through a sample of the best Yorkshire (Lowmoor) iron; but in order to obtain this result a magnetising force of no less value than **H** = 24,500 had to be employed, and the permeability, μ, was thereby reduced to 1·85, or the iron in this condition was less than twice as permeable as air. This result was obtained by turning down a cylinder of iron in the middle of its length and tapering out to the ends, so that it consisted of two cones joined together by a narrow cylindrical neck, the high induction mentioned being obtained in the narrow neck when the bases of the cones lay against the pole-faces of a powerful electro-magnet. In practice we should not, of course, work with anything approaching these figures, but should be content with a value of **B** where the metal was approaching the saturation point, which may be taken as approximately 16,000 to 17,000 for the best wrought iron.

A simple method for determining approximately the manner in which the value of the magnetic induction in, say, a soft-iron rod varies for different values of the magnetising force may now be considered.

Suppose the rod to be long compared with its diameter, we may fix it in a vertical position, with its upper end on a level with and at a convenient distance from a suspended magnetic needle, and note, by the deflections of the needle from its zero position, the manner in which the magnetisation of the rod increases or diminishes. The needle should preferably be a small piece of watch-spring, magnetised, and cemented on to the back of a small circular mirror, and suspended by a silk fibre. It should be mounted, in order to shield it from air currents, in a small glass-fronted case. A beam of light can be made to fall on the mirror, and the reflected beam falling on a scale, the movements of the spot of light so formed may be made to indicate with great exactness every movement of the needle. The iron rod being of considerable length, its lower end will be so far away that it will have practically no effect on the needle. If a coil of wire be wound over the rod, currents of gradually increasing strength can be sent through the coil, and the magnetising force being proportional in every case to the current strength, while the deflections of the needle are approximately proportional to the magnetisation of the rod, a set of fairly accurate results can readily be obtained. If it be desired to discover exactly what the increased effect due to the iron core is at every stage, it is only necessary to remove the core, and take another set of readings with the coil alone, employing a similar set of values for the current strength; and then, deducting the deflections so obtained from those previously obtained with the core in the coil, the effect due to the iron can be deduced. Or a second similar coil (without an iron core) might be placed on the other side of the needle, and the two coils being joined in series, so that they would always have equal currents flowing in them, the position of the subsidiary coil might be adjusted until its effect on the needle just balanced that of the first coil without its iron core. On then inserting the core any deflection obtained would be due to the increased effect caused by the presence of the iron.

Such results are best shown by plotting on squared paper curves similar to those given in fig. 130. This squared paper, which is exceedingly useful, is ruled with a number of equidistant horizontal and vertical lines. Let it be supposed that the line O D is divided into a number of equal parts, corresponding to the various current strengths, so that, for example, from O to the tenth division would represent five times the current strength that would be indicated by two such divisions. Let us also suppose that O M is divided equally, and that the divisions correspond to the various effects produced by the upper end of the iron rod and

FIG. 130



coil upon the needle. Let us now suppose currents of various strengths, indicated by the distances along O D, to be sent through the coil, then any one effect which the coil with its core exerts upon the needle can be measured along the line O M, and the distance thus measured marked off upon the corresponding ordinate projected from O D. The thick upper curve O A drawn through the intersecting points shows graphically, by its distance from O D, the deflecting effect produced upon the needle by the various currents corresponding to the distances along O D. Let it be further supposed that, without in any way altering the position

of the needle or of the coil, the core is withdrawn and the various currents again sent through the coil. Then the various magnetic effects of the coil upon the needle are indicated by the 'curve' O B, which, in this case, is a straight line, and which demonstrates, therefore, that the field produced by the coil is proportional to the current flowing through it. The third curve O C is particularly interesting. Suppose the magnetic effect due to the coil alone, and represented by the distance D B, to be deducted from the joint effect produced with the same current by the core and coil combined, and represented by the distance D A, then the remainder B A = D C will represent the effect produced by the core alone. And if this subtracting process is carried out along each of the ordinates, the curve O C, which shows at every point the increased effect due to the iron core, will be produced. Now it will be observed that, after a certain point has been reached, this curve becomes a nearly horizontal straight line, indicating that the saturation point of the iron has been reached, and that any further increase in the current strength does not add appreciably to the magnetisation of the core, the increase in the strength of the field developed being mainly that due to the coil itself.

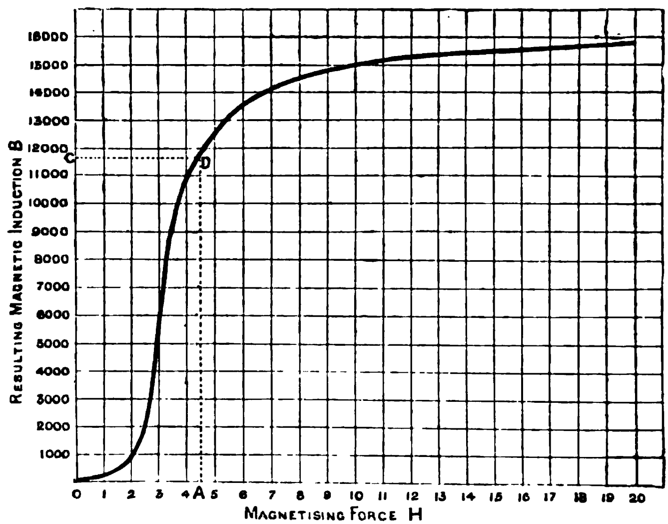
The following table gives a number of results obtained for a certain specimen of soft iron by Professor Ewing. The specimen took the form of a long thin rod, which was caused to deflect a small suspended needle or 'magnetometer' in a manner similar to that just described, and the results are perhaps more generally accurate than those of earlier date from which the curve given in fig. 130 was drawn.

H	**B**	μ	**H**	**B**	μ
·32	40	120	5·17	12,680	2,450
·84	170	200	6·20	13,640	2,200
1·37	420	310	7·94	14,510	1,830
2·14	1,170	550	9·79	14,980	1,530
2·67	3,710	1,390	11·57	15,230	1,320
3·24	7,300	2,250	15·06	15,570	1,030
38·9	9,970	2,560	19·76	15,780	800
4·50	11,640	2,590	21·70	15,870	730

In fig. 131 these tabulated results are graphically shown by the curve in which the various values of the magnetising force **H**

are plotted as abscissæ, and those for the corresponding induction B as ordinates. One side of each square represents one unit of magnetising force, and another side one thousand units of magnetic induction. For example, it will be seen from the table that a magnetising force of 4·5 developed in the iron 11,640 lines of force per square centimetre, and this particular experiment gave the point D on the curve. The position of this point was of course fixed by first taking the point A at 4·5 units distant from O, and then the point C at a distance corresponding to 11,640 units from

FIG. 131



O, and from these two points drawing lines at right angles to the horizontal and vertical base-lines respectively, these lines intersecting at the point D. The curve by its slow initial rise from the point O, followed by a sudden rise, clearly illustrates the fact that the permeability of the iron rapidly increases after a few lines of force have been projected through it, while the decided bend after the point D has been passed shows the stage at which the iron becomes saturated. It will also be observed that by increasing the magnetising force from 2 to 7, the magnetic induction was

increased to the extent of about 13,000 lines; while at a later stage a twofold increase in the magnetising force—that is to say, from 10 to 20—failed to increase the induction by 1000 lines. This emphasises the fact that it is uneconomical to work an iron core above a certain density, and that a sufficient quantity of iron should be employed to prevent the saturation point being passed.

The student should now be able to understand that in order to ensure that the armature of an electro-magnet similar to that illustrated in fig. 128 shall be capable of transmitting a large percentage of the number of lines of force which pass through the core, it must at least be equal in permeability and correspondingly massive. It should certainly be equal in section to the core. It will be seen that the coil is divided into two sections, placed one on each limb or leg of the core. The direction of winding is such that, were the core straightened out and the coils pushed together so that their ends meet, they would form one continuous coil or helix; otherwise the tendency would be to develop similar instead of dissimilar poles at the extremities of the core. The iron should preferably be the best and softest procurable, and should be bent (preferably without hammering) so that the poles are brought together; a comparatively large number of the lines of force will then pass through the space between the poles when the armature A is removed. The surfaces in contact should fit as truly as possible, so that there is the minimum air space between them. Sharp corners or edges should be avoided, and, since the natural shape of the lines of force is circular, the whole should approximate to the circular form, when there will be little tendency for the lines of force to 'leak out' of the iron and complete their circuit through the air space.

Such horseshoe electro-magnets are frequently constructed to sustain a weight. The sustaining power is not, however, necessarily in strict proportion to the magnetising force, or even to the total number of lines of force produced, as this power depends also upon a number of secondary considerations (such as the shape of the pole-pieces or extremities of the core, the dimensions and surface of the armature, and the method of applying the weight to be sustained), some of which do not require to be taken into account when estimating the electro-magnetic field itself.

The weight can be suspended from a hook fixed to the middle of the armature, so that the pull upon the two poles is equal, the sustaining power being measured by the weight which can be supported by the armature without causing its separation from the magnet.

It is, however, frequently preferable, for convenience of construction, as in the case of some forms of dynamo-electric machines, as well as in telegraphic and other similar apparatus, to build up an electro-magnet in which two straight cores are yoked together by a piece of soft iron which is screwed or bolted to them. The yoke must naturally be massive, and the surfaces fit truly to avoid as far as possible the introduction of a magnetically resisting air space.

In addition to its high permeability, pure soft iron has another property which recommends its adoption for the cores of electro-magnets, and that is its low 'retentivity,' for in many cases electro-magnets are required to develop as strong a field as possible at some particular point directly the current commences to flow, and to lose or be deprived of all traces of magnetisation on the cessation of the current. Steel, as we have already seen, always retains a large proportion of the magnetisation imparted to it. Hard and impure iron have similar properties, inferior only to steel itself. There is no doubt that these properties of permeability and retentivity are very largely governed by the molecular structure of the iron or steel, and by the greater or less rigidity obtaining among the particles of the metal. In fact, the two properties of permeability and retentivity are to a great extent linked together; for all qualities of iron or steel through which it is difficult to urge the lines of force, or to magnetise, are found to be correspondingly obdurate when it is sought to demagnetise them, or deprive them of magnetisation. There is, therefore, a double gain in employing pure soft iron, for not only is its permeability greater, but its retentivity is also less than that of impure or hard iron.

On the other hand, in selecting a material for permanent magnets the principal thing to be considered is the retentivity, which, of course, should be as high as possible. No substance has yet been found which is, in this respect, superior to good

hard steel. Some specimens of steel have been made so hard that efforts to appreciably magnetise them have proved futile. One of the most remarkable features to be observed in this matter is the extraordinary effect produced by the admixture of a small—one might almost say a minute—proportion of other, or foreign, substances with the iron. Just as a fractional proportion of iron or other metal added to copper causes a large increase in its electrical resistance, so the addition of carbon, tungsten, phosphorus, sulphur, arsenic, &c., to iron reduces its permeability and increases its retentivity. In the case of ordinary steel the retentivity is evidently due, in a great measure, to the presence of carbon, and, with a bar of good magnet-steel, the permeability is so feeble, and the retentivity so great, that it is impossible, by electro-magnetic induction, to upset the molecular arrangement in the interior of the bar, so that the magnetisation is in reality little more than skin-deep. This can be easily proved by magnetising a small piece of very hard steel and then immersing it in dilute sulphuric or hydrochloric acid. In a few moments the surface of the metal will have been dissolved, and on withdrawing it from the liquid all traces of magnetisation will have disappeared. Consequently, it is preferable, in making a large permanent magnet, to build up a number of thin strips of steel cut to size and then magnetised separately. On fastening them together, the built-up, or 'laminated,' magnet will be found capable of producing a far stronger field than can be obtained with any solid magnet of similar dimensions. It should, however, be added that in building up such a compound magnet there is no advantage in employing *brass* screws or bolts to fasten the individual magnets together as is usually done. In fact, this plan cannot but disperse the lines of force passing through the magnets, and therefore weaken, more or less, the polar strength. Iron screws or bolts are mechanically as well as magnetically preferable.

It is interesting to notice that specimens of steel have been made, containing 12 per cent. of manganese, which it has been found practically impossible to magnetise even under the influence of a very powerful field. Apparently the molecular rigidity is so great that no ordinary magnetising force can overcome it and make the particles take up new positions; and this assumption is

partly borne out by the fact observed by Mr. Hadfield (who introduced this particular kind of steel) that long-continued vibration appreciably increases its susceptibility to magnetisation. Similar results follow when the proportion of carbon, phosphorus, sulphur, &c., mixed with the iron exceeds a certain small limit, while the admixture of even a small percentage of antimony suffices, it is alleged, to destroy all trace of magnetic properties. There should certainly be a large field of practical utility open to the economical manufacture of unmagnetisable iron. For example, the bed-plates of certain types of dynamos (now, however, obsolete so far as the manufacturer is concerned) are frequently separated from the field-magnets by huge slabs of zinc or brackets of gunmetal because, otherwise, the bed plates would form what may be called a magnetic short-circuit between the poles of the field-magnets. Zinc is mechanically much weaker than iron, and this, added to its very much higher price, renders its use objectionable. Gunmetal, although much stronger than zinc, is still more expensive. To avoid the difficulty, comparatively small two-pole dynamos are rarely designed with their pole-pieces downwards, but are turned about so that the bed-plate is connected to the yokes or magnetically neutral portions of the field-magnets. Under such circumstances scarcely any of the lines are wasted by passing through the bed-plate.

Reverting to the question of magnetic inertia, it may be mentioned that any cause which may operate to set up molecular vibrations in a piece of iron or steel facilitates either magnetisation or demagnetisation—that is to say, if the metal is placed in a magnetic field and vibrations then set up in it, it will be more readily and more powerfully magnetised than would be the case were the vibrations not set up, and, conversely, a magnet loses its magnetisation by being set in vibration, due to the fact that facilities are thereby afforded for the individual particles, which are themselves magnets, to partially rotate and form little closed magnetic circuits in the mass of the metal. These vibrations can be caused by heating, hammering, twisting, or any other similar violent treatment. Hence permanent steel magnets should always be placed down gently, and never dropped or thrown down, otherwise the magnetisation will be more or less destroyed. A magnet

raised to a red heat loses its magnetisation entirely, and this can easily be demonstrated by heating a magnetised sewing-needle in a gas flame; and, further, while at that temperature it is no longer attracted by a magnet, but acts similarly to a non-magnetic metal. It, however, recovers its magnetic properties on cooling down, but does not, of course, recover any magnetisation which may previously have been imparted to it.

By adopting the precautions referred to, permanent steel magnets can be made capable of sustaining more than thirty times their own weight, and a description of the method practically adopted for the manufacture of permanent steel magnets capable for some years of supporting about twenty-five times their own weight may prove serviceable. In this case the best tungsten steel is employed. It is heated gently to a dull red heat and hammered into the required shape, care being taken not to raise the temperature too high, or the tungsten may be volatilised. Even a small magnet may therefore require to be placed in the fire several times before the necessary shape has been obtained. This process being completed, the steel is then hardened by being first placed in a close fire out of contact with air so as to ensure uniform heating and to prevent the formation of a hard scale of iron oxide. It is then dipped into a water bath. This latter process must be carefully attended to, or the metal will be twisted or otherwise distorted. It should be held vertically, and, if of the horseshoe pattern, its extremities should be dipped in first, and then steadily lowered into the water. The next process is that of polishing, after which it is passed a few times over the poles of a large and powerful permanent magnet, the steel being turned over once or twice so as to magnetise both faces. Of course, a large electro-magnet, with a powerful current circulating through its coils, can be employed, but the permanent magnet is quite as efficient, provided it be sufficiently powerful.

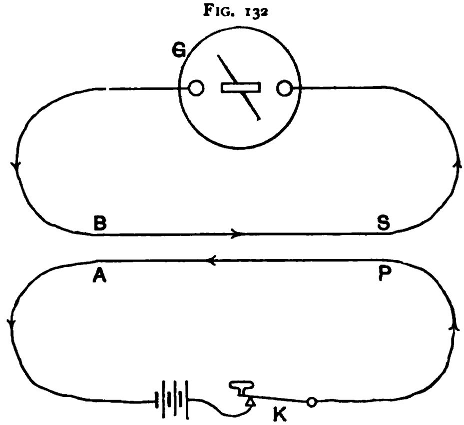
Concerning the difficulty of magnetising very hard steel to any great depth below the surface, it may be interesting to mention briefly some experiments which we have performed, using sulphuric acid solution to dissolve the surface particles of the steel. Our experiments were suggested by the publication by Professor Hughes of his classical papers, which threw considerable light on

the fundamental principles of magnetism, and constituted a great advance in the practical application of the science. One of the most beautiful experiments was that in which a steel rod, or, better still, a steel strip, was slightly twisted to the right and then magnetised by being passed over the pole of a bar magnet in one direction. It was then similarly twisted to the left and oppositely magnetised by being passed over the same pole in the reverse direction. Hughes found that when the torsion was released, and the strip assumed its normal condition, it gave no evidence of magnetisation, but by simply twisting it either to the right or to the left it at once gave evidence of magnetisation, and in the same sense as that imparted to it while under the particular twist—that is to say, the polarity could be reversed by twisting first to the right and then to the left. In our experiments we sought to bring about this superimposed polarity without mechanically altering, by twisting or otherwise, the position of the particles of steel, and to demonstrate the success of the experiment by chemical means. For example, a small steel rod was raised to a red heat and plunged in water while in a strong magnetic field. It thus became hardened and at the same time powerfully magnetised. It was next drawn gently over one pole of a powerful magnet in such a direction as to magnetise it in the opposite sense to that previously imparted, the process being continued until there was no external evidence of magnetisation. The rod was then immersed into a sulphuric acid solution, in line with a magnetometer. Immediately after immersion there was no deflection of the magnetometer needle, the rod behaving similarly to a piece of unmagnetised steel. In a very short time, however, the magnetometer needle began to move slowly, say, to the left, the deflection gradually increasing up to a certain maximum from which it as gradually fell to zero, when it was found that nearly the whole of the steel rod had been dissolved. Were the process to which the steel rod had been subjected unknown, it would appear that the mere immersion in the solution and the consequent chemical action had imparted magnetisation to it; but, of course, the fact is that the outer layers only were reversed in magnetisation, and to a sufficient extent to just neutralise the magnetisation of the interior of the rod, which remained unaltered. As the outer layers were

dissolved, the interior magnetisation preponderated more and more, until when the whole of the exterior magnetised shell had been dissolved the maximum deflection was obtained. The subsequent fall in the deflection resulted from the gradual dissolution of the interior portion. A number of other experiments were performed, some of them of a more or less fanciful character, but all involving the same principle.

We have stated frequently—so frequently, in fact, that we feel it is almost necessary to apologise for repeating the statement—that when a current of electricity is set up in a wire, an electro-magnetic field is almost immediately generated in the region surrounding

FIG. 132

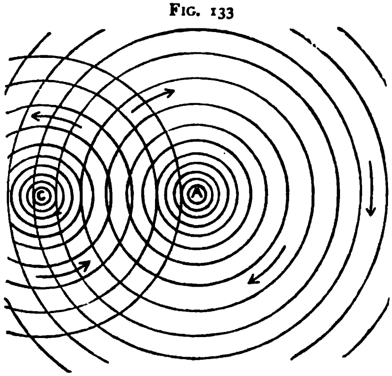


that wire. But the converse of this is also true, viz. that when an electro-magnetic field is suddenly set up around a wire, there is a tendency for a current to be generated in that wire *during the setting up of the field*, and if the wire forms part of a complete circuit a current will flow along it. The source of the field is immaterial: it may be a permanent magnet, a straight wire or a helix carrying a current; all that is essential being that the lines of force should be thrust across the wire, or that the wire should be moved in such a manner as to cut the lines of force *transversely*. As an instance, let A P, B S (fig. 132) be two wires running side by side for a certain distance, each forming part of a complete

circuit. If a current is started in A P, lines of force will immediately start from its centre or axis, in the form of widening circles, and, cutting the second wire, B S, set up an electro-motive force therein and, in consequence, generate an electric current. It is only, however, while the lines of force are actually cutting the second wire that the E.M.F. is developed, and as this cutting ceases immediately the current in A P arrives at its full strength, the induced current lasts but for a moment. In direction it is opposite to that of the current in the wire A P. While the original current is steady many of the lines of force due to it are embracing the adjacent wire B S, but, being relatively at rest, they have no effect thereon.

When the current in A P is stopped, all the lines of force collapse upon it, and those which extended beyond the wire B S again cut it, and thereby induce in it another momentary current. But since the lines now cut the wire B S in the opposite sense (for they approach it from the opposite side), the resulting current is in the opposite direction to the previous one—that is, it is now in the same direction as the inducing current which was flowing in the wire A P. By noting the direction of the lines of force due to the inducing current, and the direction in which they must coil round the wire B S during the time they are passing it, we might predict the *direction* of the induced current in either case. It is somewhat difficult to make this clear by diagrams, but an analogy may assist us to a great extent. When any small body is dropped on the surface of still water it breaks that surface into a series of ripples which take the form of ever-widening concentric circles as in fig. 133, where A is the point of generation. In such a manner do the lines of force spring into existence from a wire, only with far greater rapidity, and it is difficult in either

FIG. 133



case to fix a limit to their extent if the medium (the water or the ether) is not limited.

Now, if these water ripples meet any obstruction, a post for instance, at the point C, they set up around it a series of circular ripples, feebler, perhaps, but precisely similar in character to themselves. It is difficult at present to say with certainty exactly what happens in the case of the electro-magnetic lines of force, but we can safely use the analogy for the purpose of demonstrating that the direction of the lines of force round the wire in which the current is induced is opposite to their direction round the inducing wire. For, suppose, as in the case of the lines of force, the original ripples round A to have what is called a positive direction—that is to say, that the ripples circulate in a right-handed direction after the manner of the hands of a clock, as indicated by the arrows in the figure; then, since that direction would not be reversed by reflection at the obstacle C, they must go round C left-handedly or contrary clock-wise. Now, if these were electro-magnetic lines of force we know (Chapter IV.) that their direction would indicate a current flowing *downward* through A, and *upward* through C, and thus we can readily perceive how the starting of a current in one wire gives rise to an *inverse* one in a neighbouring wire. Further we see that it is only while the original ripples generated from A are *passing* the point C that these secondary ripples can be generated or called into existence, and we may again picture to ourselves how it is that a current is induced in a wire only during the time that the current in the neighbouring wire is attaining its full strength.

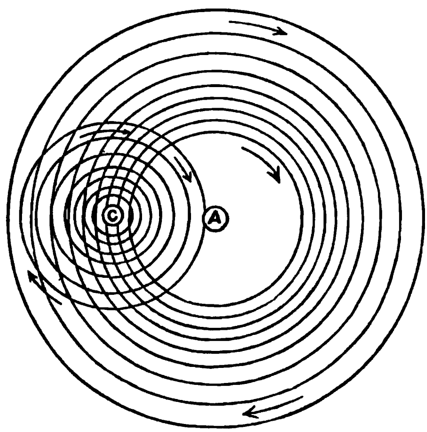
Let us now suppose it possible to cause a series of ripples to collapse upon the point A, in the same manner that we imagine lines of force to collapse upon a wire. Before arriving at A they would meet with C, and, as before, generate a series of secondary ripples, but in this case their direction round C and A would be the same, for now they approach C from the opposite side, that is, the side remote from A. Again assuming the ripples to have a positive direction, the arrows in fig. 134 show that their direction will be the same round each, and if A and C were wires and the circles lines of force, the current in each wire would be flowing downward through the paper. It thus becomes easy to

imagine how the stoppage of a current in a wire induces in a neighbouring wire a current in the *same* direction as itself. The wire in which a current is induced is called the secondary, and the one which carries the inducing current is termed the primary wire.

Further, it should be noted that the induced current must always have such a direction that it opposes the action which produces it, otherwise the induced and inducing currents would increase without limit, i.e. the conditions would be unstable.

Now, if in fig. 132 the wire A P while carrying a steady current, were suddenly brought close to B S, or if B S were suddenly brought close to A P, the lines of force would cut B S in precisely the same manner as they did when a current was started in A P. The result would therefore be the same—that is, a momentary current would be developed by induction in B S in the opposite direction to that of the current in A P. Furthermore, if the two wires were then suddenly moved asunder, B S would be cut by the retreating lines of force just as it was cut during the stopping or the dying away of the primary current, and a direct induced current would therefore be the result.

FIG. 134



These induced currents bear a very simple ratio to the currents producing them. The E.M.F. in the secondary wire is proportional to the number of lines of force which cut it, and also to the rate at which they cut it. Now, the number of lines of force may be increased by increasing the strength of the current in the primary wire, or by adding to the length of the wires in proximity. In the latter case, however, it is more convenient to wind the longer

wires in spirals or helices, when the effect will be similar to that which would result from two long straight wires. It is evident that the two wires should be as close together as possible, otherwise those lines of force very near the primary wire would not reach the secondary wire at all, and would, therefore, fail to produce any effect therein. In some cases when it is desired to obtain a powerful induced current, the primary and secondary wires are wound in the form of concentric helices, and an iron core is inserted to increase the number of lines of force which cut the secondary. Having by such means made the number of effective lines as high as possible, the only other thing to be done in order to increase the secondary E.M.F. is to make the rate at which the secondary wire is cut by these lines as great as possible.

Now supposing the two wires A P, B S (fig. 132) to lie quite close together, and that it be possible for the current in A P to be started and to arrive at its full strength instantaneously; the rate at which its lines of force would cut B S would then be a maximum, and we should get a heavy but extremely brief induction. In practice, when a current is started in a wire it does not rise to its full strength instantaneously, nor does it stop suddenly; time is taken for the lines of force to spring into existence and to die away, and under certain conditions this time may be considerable. To understand the principal cause of this sluggishness, let us refer again to fig. 133 and further study the case of the water ripples. A little thought or experiment will make it evident that the secondary ripples round C will quickly reach the point A, and if the body which caused the disturbance is still there, will set up around it ripples in the same sense as the original ones. Now, suppose two wooden balls, A and B, were dropped into the water at the same moment close together and equidistant from C, they would set up ripples round C, each to the same extent and in the same sense; in fact, the number round C would be doubled. But still stronger is the effect of A and B round each other, and (still assuming a positive direction just as we do for lines of force) the direction of the ripples so set up round each will be opposite to those which it generates. In the same way if a primary wire is looped into two convolutions, A and B, they

will generate round an equidistant loop of the secondary, c, just double the number of lines of force which one will; but they also react upon each other, each setting up round the other lines of force in that direction which would generate a current tending to stop the primary one, the result being that this primary current does not rise so rapidly to its full strength. This retardation increases as we increase the number of convolutions; in fact, it varies directly as the square of the number of convolutions into which the primary wire is looped, because the number of lines of force threading the loop is proportional to the number of convolutions, and the current induced in the loop when these lines vanish is proportional to the product of the number of lines and the number of convolutions. Therefore the retardation in a coil of 100 turns would be 100 times as great as in a coil of 10 turns.

In a precisely similar manner the reaction of adjacent convolutions prevents the instantaneous *stoppage* of a current; for, at the moment of disconnecting the battery or other current generator, lines of force collapse upon each convolution, and in so doing they cut the other convolutions and generate a direct induced current which will also vary as the square of the number of turns, and tend to prolong, or more correctly speaking to retard the disappearance of, the primary current.

The electro-motive force resulting from this collapsing of the lines of force may be, and usually is, much higher than that which maintains the original current. This may easily be demonstrated, for supposing the battery used to consist of ten Daniell cells, then, if the poles are connected by a short piece of wire, no spark, or, at the most, a very feeble one, is observable when the circuit is closed and opened quickly. If this same battery is made to send a current through a coil of many turns of wire, although its resistance may be high and cause the current to be comparatively weak, yet on breaking the circuit a spark will be observed. This is due to the fact that the lines of force fall back so quickly upon their respective convolutions in the coil, that they cut the adjacent convolutions with sufficient rapidity to generate a momentary E.M.F. high enough to produce a current sufficiently strong to volatilise a portion of the metal, and to maintain the current across the vapour-filled space for a brief

interval, even after the wires are moved asunder. This effect is still more striking if in a dark room contact is broken between a wire and a mercury surface, when a little of the mercury is volatilised; and, since the effect of iron placed in the vicinity is to increase the number of lines of force which are active, the spark can be increased enormously by placing a core inside the coil.

The term 'self-induction' has been given to this action, which prevents the instantaneous rise and fall of a current, and it will be evident from what has been said, that, in the case of a simple straight wire, this phenomenon is almost imperceptible, and that, in order to make the self-induction of any circuit a maximum, the wire should be wound into as many convolutions as possible, and be provided with plenty of iron.

In some cases it is desired to design electro-magnets which shall be affected as little as possible by brief, sudden fluctuations of the magnetising current. It is manifest that in such a case the electro-magnetic inertia—that is, the self-induction—must be made high by using a long and massive core and a great number of turns of wire; for as we have seen, self-induction prevents a rapid rise or fall of the current in just the same way that the inertia of matter prevents any instantaneous change in its motion. If, on the other hand, an electro-magnet is required to be quick-acting, or to be very sensitive to any variation in the current, self-induction should be as low as possible, and in order to obtain this, the coil should consist of as few turns of wire as possible, and the core should be short, and not form a complete circuit of iron.

The fact that when a conductor is cut by lines of force a current is generated therein if it forms part of a complete electrical circuit enables us to compare the strengths of different fields. For example, we can place a small exploring coil which encloses just one square centimetre in a certain field with its plane at right angles to the lines of force, when it will enclose lines of force equal to **B**, or the number per square centimetre in the field. By suddenly removing the coil from the field it will cut all the lines of force which it previously embraced, and the resulting current will be proportional to this number. Consequently if the coil be similarly placed in, and removed with equal suddenness from, a second field, the second current so obtained will also be

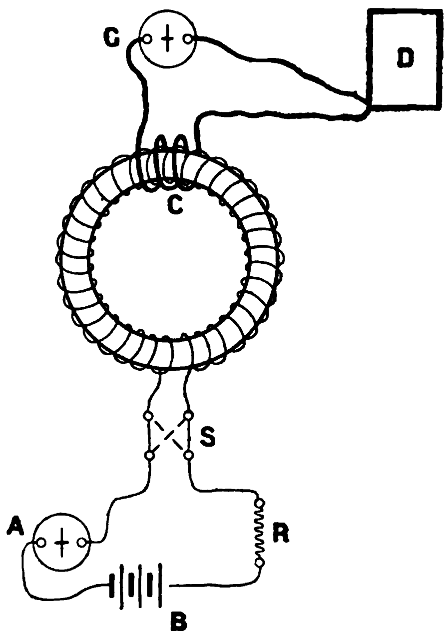
proportional to the strength of that field, and by comparing the strength of the two currents we can effect a comparison between the strength of the two fields. Instead of removing the coil it may be suddenly turned through a right angle, when its plane will lie parallel to the lines of force, in which position it will embrace none of them; or it may be turned through 180 degrees, in which case twice the current strength will be obtained on each occasion, since the coil will cut the whole of the lines of force which it embraced, twice instead of once only. The resistance of the electrical circuit and all other conditions must of course remain the same during the experiments on both fields. To put the matter more precisely, the electro-motive force generated in the coil will be proportional to the number of convolutions in the coil, to the number of lines of force which it cuts, and to the speed at which it cuts them; while the strength of the resulting current will be proportional to this electro-motive force, and inversely proportional to the resistance in the circuit.

Again, instead of moving the coil, the lines of force may be suddenly removed from it, or, better still, they may be reversed; and this latter method is perhaps the best of all for measuring the value of the induction in a sample of iron with various magnetising forces. The iron is preferably made in the form of a continuous ring, and overwound evenly with a coil through which a current may be sent and reversed; and the current strength and number of convolutions per centimetre n being known, the value of the magnetising force may be calculated from the formula $\mathsf{H} = \frac{4 \pi \mathrm{C} \times n}{10}$, where C is the current strength in amperes. If the iron is homogeneous, the magnetic induction **B** will be the same in every portion of it, and a small coil wound over the iron at any point will embrace all the lines passing through the iron. Then by reversing the current the iron is suddenly demagnetised and magnetised in the reverse direction, and all the lines of force so made to vanish and start in the opposite direction must cut the little coil and generate a current therein.

In fig. 135 we show a simple arrangement of apparatus suitable for experimenting by this method, which has been used by a number of investigators. In the primary circuit is placed a

battery B, a resistance coil R for varying the current strength, and a galvanometer or ammeter A for measuring the current, all being joined in series with the magnetising coil which is wound uniformly all round the iron ring. The switch S enables the current to be started, stopped, or reversed in direction. The secondary circuit consists of the small coil C, a galvanometer G, and a coil wound on a rather large wooden frame D. G is

FIG. 135



preferably a 'ballistic' galvanometer, having a somewhat massive needle suspended by a silk fibre, it being essential that the whole of the transient induced current shall flash through the coils before the needle has moved appreciably from the zero position. Under such conditions the deflection of the needle will be proportional to the total quantity of electricity flashed through the coil, independently of a small variation in the time occupied in passing

on different occasions, since the needle receives the whole of the impulse while in the most sensitive position. A mirror attached to the needle enables the deflections to be read by the movements of a spot of light, as previously explained. The coil on the frame D, which is permanently connected in circuit, enables the galvanometer to be standardised. When laid flat on a table it embraces a known number of lines of force due to the earth's magnetism (the area of the coil and the vertical component of the earth's magnetism being known), and if turned suddenly over it will cut all these lines twice, and the deflection caused by the resulting current being thus due to an inductive effect of known value, all other deflections can be compared with it. The small coil C should preferably be wound next the iron, otherwise it may embrace a considerable space containing air, copper wire, &c., and many lines of force will pass through this space and be embraced by and cut the secondary coil, especially when the iron has its permeability greatly reduced by being strongly magnetised.

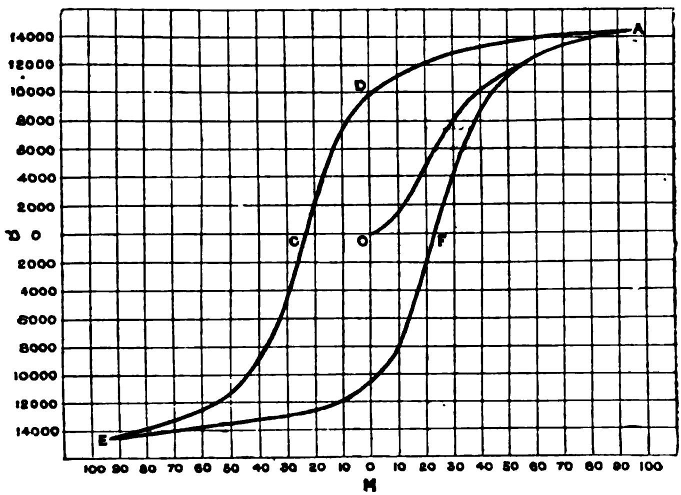
By means of such a set of apparatus, it is possible to study the manner in which the magnetising force, magnetic induction and permeability, vary in the case of any sample of iron or steel, and the results can be conveniently plotted in curves, which for soft iron would be approximately similar to that given in fig. 131. For hard iron, cast iron, or steel, the curve would rise with a gentler slope.

In such a case as that of the field-magnet core of a dynamo machine, where the core is constantly magnetised in one direction only, permeability is practically the only quality of the iron which need be taken into account. But another quality of even greater importance has to be considered with respect to an iron core (such as an armature core), where the magnetisation is repeatedly and rapidly reversed, for this reversal, involving as it does the changing of positions of the particles of the iron, cannot be effected without an appreciable expenditure of energy, which is converted into heat. The name 'hysteresis' has been given to that property of the iron in virtue of which a definite amount of energy has to be expended in order to change the position of its particles, and the energy so expended varies with the intensity of the magnetisation, the mass of the iron, the rigidity with which the particles

are set in position, and the rapidity with which the reversal is effected.

In fig. 136 we give a curve which will serve to illustrate this phenomenon, and which is based upon the experiments of Professor Ewing. It was obtained by experimenting upon a specimen of annealed pianoforte steel wire, and plotting the various values for the magnetising force, **H**, and the resulting magnetic induction **B**. The first part of the curve, starting at O and ending at A, rises similarly to that shown in fig. 131. It will be observed that when **H**

FIG. 136



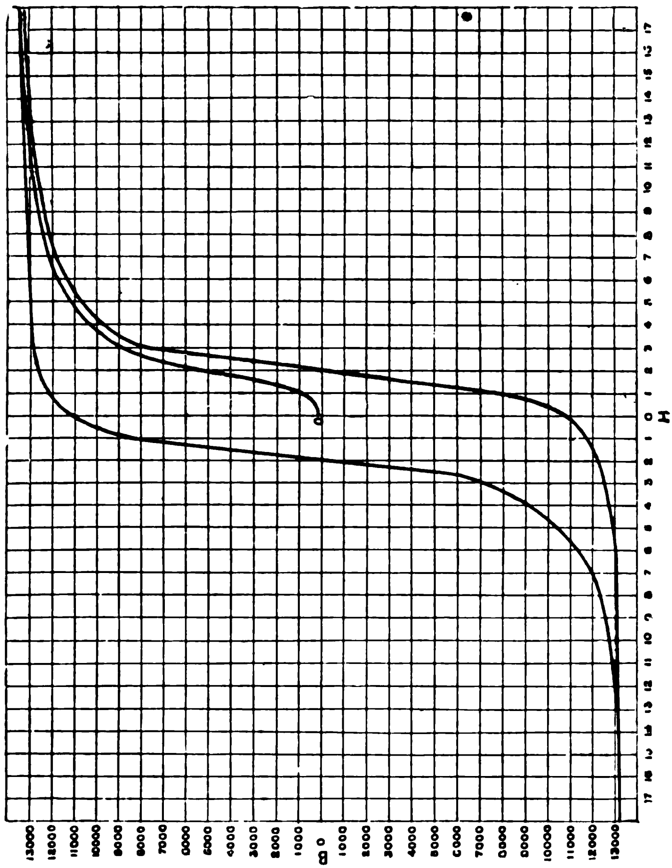
was no less than about ninety-five units, the number of lines urged through the specimen barely exceeded 14,000 per square centimetre. When the point A had been reached the magnetising force was reduced step by step and the induction remaining at every step observed. The curve from A to C was thus obtained. If no energy were expended in the process of turning the particles into new positions, this descending curve would coincide with the ascending one; but it will be observed that it lies considerably to the left of it, and as indicated by the ordinate O D, no fewer than 10,000 lines per square centimetre remained in the steel when

the magnetising force **H** was reduced to zero. The length of this ordinate O D gives a measure of the retentivity of the steel. In order to demagnetise the specimen it was necessary to apply a negative magnetising force (by reversing the direction of the current), and complete demagnetisation was effected when $\mathbf{H} = -23$ approximately, as indicated by the length of the line O C. Dr. Hopkinson has happily applied the term 'coercive force' to the force (as measured by O C) which it is necessary to apply in order to demagnetise any specimen after it has been magnetised to any given degree, and this coercive force can be definitely indicated in terms of **H**. From this point where $\mathbf{B} = 0$ the negative magnetising force was increased until it had the same value as was previously given to it in the opposite direction, when the value of **B** was the same as on that occasion, but negative instead of positive. From this point E the magnetising force was diminished step by step, then reversed and increased positively as before, thus giving the ascending curve E F A. It will be evident that the area E C A F enclosed by the outer curves will for any given case become greater as either the maximum induction reached, or the coercive force of the specimen, is increased; and it has been shown that for any specimen the energy in ergs wasted in the complete cycle of operations by means of which the curves E C A, A F E are obtained, is proportional to the area of the figure enclosed by those curves. If the curve be plotted to an appropriate scale, the area enclosed divided by 4π gives the number of ergs per cubic centimetre of iron wasted during one complete cycle—that is to say, in changing the magnetisation of the iron from its positive maximum to its negative maximum, and then carrying it back again to its positive maximum. As an instance of the effect of hardening, it may be mentioned that a similar specimen of pianoforte steel wire, when made very hard, had a coercive force of over 40 units, which value would greatly increase the area enclosed by the curves and correspondingly increase the hysteresis loss.

It will be seen that the coercive force, which depends chiefly upon the nature of the material employed, is the principal factor in determining the amount of the energy lost by hysteresis, and hence the importance of selecting a material in which the coercive

force has a low value, for use in those cases where the magnetisation is repeatedly reversed. As might be expected, the coercive force of soft iron is much lower than that of steel or hard iron,

FIG. 137



and this will be evident from an inspection of fig. 137, which is also based upon Professor Ewing's experiments. It should be noted that in order to obtain a clearer figure the magnetising

forces are plotted to a much greater scale than those in fig. 136, so that the two areas must not be directly compared. The value of the coercive force did not in this case exceed 2 units.

Both of these hysteresis curves were obtained by experimenting with a ballistic galvanometer after the method illustrated in fig. 135, the only difference being that the specimens were in the form of long straight wires instead of rings, with the coils wound over the middle portion of the wire.

It is interesting to note that the soft-iron specimen possessed a little remanent magnetism, so that the initial curve in fig. 137 does not start exactly at zero, but a short distance above it.

CHAPTER VIII

DYNAMO-ELECTRIC MACHINES (ALTERNATE CURRENT)

IN the preceding chapters we have dealt with some of the principal laws of electric currents, and the more striking phenomena connected with them. The student will not have failed to notice two important facts: (1) That when a wire through which a current is passing is placed in a certain position in any electromagnetic field it has impressed upon it a definite mechanical force tending to move it into another part or out of the field; and (2) when a conductor is mechanically moved in a field transversely to the lines of force traversing that field, a certain electro-motive force is developed, which sets up a current in the wire if its two ends are connected. Extensive use is made of both these effects in practice, and on a very large scale. Machines which are constructed to transform energy which exists in the form of electric currents into energy in the form of mechanical motion, and, conversely, machines which are able to transform energy in the form of mechanical motion into energy in the form of electric currents, can be included under the generic head of 'dynamo-electric machinery.'

We shall first consider machines of the latter class, which are commonly known by the shorter name of 'dynamos,' deferring a consideration of the other class until an opportunity offers for dealing with such apparatus under the more generally adopted title of 'motors.'

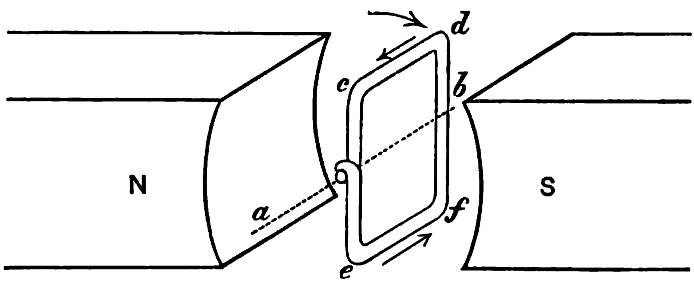
In every machine for the conversion of energy there is always a certain amount of loss attending the conversion; in other words, less energy appears in the new than existed in the original form. The more perfect the machine, the less does this loss become, so that a theoretically perfect machine would be one in which there

is actually no loss at all. It is absolutely impossible to construct such a machine, but in every case the chief aim of the engineer should be to make the loss as small as possible, or, in other words, to make the machine as 'efficient' as possible. The proper way of doing this is to start with the fact established in accordance with the doctrine of the 'conservation of energy,' that energy can never pass out of existence or be destroyed; that, therefore, the whole of the energy put into the machine reappears in some shape or form, although only a part appears in the exact state in which it is desired. Steps should then be taken to ascertain exactly what form the other or undesired part takes, and the designer of the machine should study how to reduce that same part, which may be called 'waste,' to a minimum: In all machines which have moving parts, a certain percentage of the energy takes the form of heat, due to friction at the bearings and other surfaces which come into contact. Every dynamo has moving parts, and is therefore subject to loss from this cause, and the well-known methods of reducing friction by good workmanship and design, the judicious application of oil or other lubricant, and in special cases the use of ball bearings, are taken advantage of to minimise the loss. But there are many other causes besides mechanical friction which operate to reduce the efficiency of a dynamo; they are mainly due to electro-magnetic phenomena, and careful study is required in order to discover how to eliminate or minimise them, although in some instances the loss may be readily localised, because, like friction, these phenomena convert a certain amount of the original energy of mechanical motion into heat. One of the principal features, then, by which a dynamo is judged is its efficiency, or by the ratio of the energy reappearing as electric currents to the total amount given mechanically to the machine.

We will start with the consideration of the simplest type of dynamo-electric machine, and, observing its weak points, endeavour to trace its development into a practical and highly efficient piece of apparatus. Now, it is only during the time that the lines of force of a field are being cut by a conductor that an electro-motive force is induced in that conductor; therefore, in order to obtain a continuous current, or a very rapid succession of currents, it is evident that either the conductor or the field must be kept

continually in motion. Let us first study the case of a fixed field and a moving wire, assuming, for the moment, that we have a strong and fairly uniform field, produced by the opposite poles of two large permanent bar-magnets placed near to each other, or by any other convenient means. A uniform field has been already defined to be one in which the lines of force are straight, parallel, and equidistant. It is not easy to obtain a strong uniform field of any great extent, so that the most convenient way of continually cutting lines of force is to cause the conductor to move in a circular path, within the limits of a powerful field of comparatively small area. For instance, if the wire is bent into a single rectangular coil, as shown in fig. 138, it may be placed in the field with its plane at right angles to the direction of the lines of force

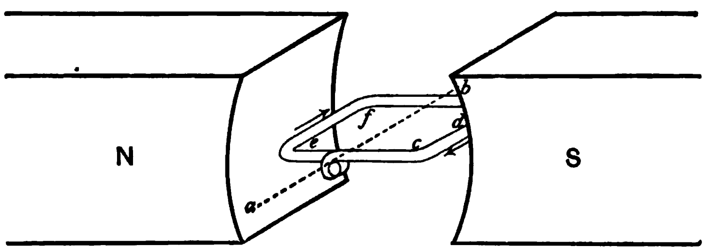
FIG. 138



so that as many as possible of these lines are made to pass through it. If, now, this coil is turned suddenly through an angle of 90° about the axis *a b*, its plane will then lie parallel to the lines of force, as shown in fig. 139, and it is obvious that none of the lines of force now pass through the coil. In the act of turning, both the top and the bottom limbs, *c d* and *e f*, cut a certain number of lines, setting up thereby an electro-motive force in the wire; but, as these two limbs of the rectangle cut the lines from opposite sides, the direction of the resulting currents in them is opposite. In the limb *e f* the direction is, during the quarter of a revolution, from front to back, and in the limb *c d* from back to front. Both currents, therefore, pass round the coil in the same direction. The side limbs of the rectangle—that is, *c e* and *d f*—simply slide, or

slip, through the lines of force, and do not *cut* them; they therefore have no current induced in them, and, while adding to the resistance of the loop, are useless, except for the purpose of completing the electrical circuit. The student may now, with advantage, again read the paragraphs on page 280, which indicate how the direction of an induced current can be predicted, or he may apply an ingenious rule known as Fleming's right-hand rule. By this rule, the thumb, forefinger, and middle finger of the right hand are held mutually at right angles; then if the forefinger points in the direction of the lines of force, and the thumb in the direction of motion, the middle finger will point in the direction of the induced E.M.F. In the present case the lines of force pass from left to right, and the

FIG. 139

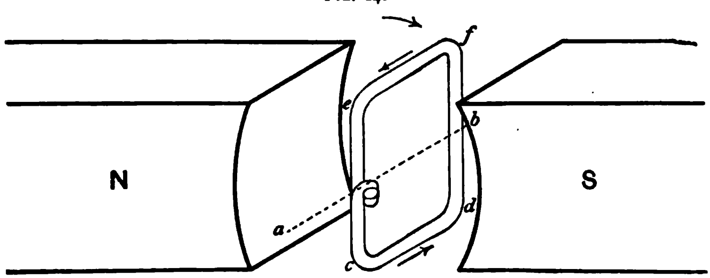


number cut by each active limb, so far, is half the total number originally passing through the rectangle.

When the rectangle is turned through another 90°, so that the limb which was at first uppermost is now at the bottom, as shown in fig. 140, it has the maximum number of lines of force suddenly thrust through it again; another induced current is the result of this second quarter of a revolution, and as, during the movement, both the horizontal limbs cut the lines from the same side as they did in the first movement—that is to say, the one limb still cuts downwards and the other still cuts upwards—the direction of the current is the same as that developed during the first quarter of a revolution. Further, as the number of lines of force cut is in each case the same, the induced E.M.F. is also the same for each similar position, provided the rates of moving are equal.

If, therefore, the rectangle is rapidly turned at one sweep from its original position in fig. 138 through 180°, a current will be induced, in the direction shown by the arrows, during the whole of that movement. If the rotation is continued, on passing the 180° the horizontal limbs again begin to cut the lines of force, but they then cut them from their opposite sides, or in the opposite direction to that during the first half-revolution. The resulting current is therefore in the opposite direction along the active limbs, as compared with the previous current, but of precisely the same strength at corresponding positions if the motion is uniform. The arrows in fig. 140 show the direction of the current during the second half of the revolution. A continuous rapid rotation of

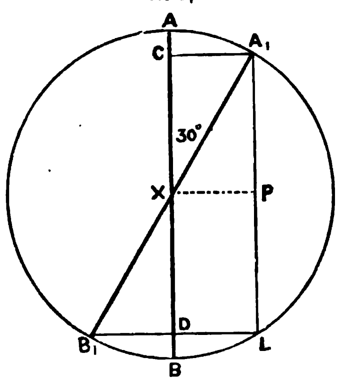
FIG. 140



the rectangle, then, will give rise to a series of currents alternating in direction, two distinct currents being generated during each complete revolution, the reversal taking place every time the rectangle passes the points at which its plane is at right angles to the lines of force—that is to say, those positions in which it embraces the maximum number of lines of force. It must be clearly understood that at the moment of reversal in the direction of the current—that is to say, when the plane of the rectangle is at right angles to the direction of the lines of force—the E.M.F. falls to zero, and consequently for an instant there is no current circulating round the rectangle; the arrowheads in figs. 138 and 140 represent the direction of the current along the active limbs a moment after the rectangle has passed the positions shown in the figures.

Supposing both the field and the speed of rotation to be uniform, the question arises whether the E.M.F. is also uniform during, say, the whole time of a half-revolution. As the induced E.M.F. at any and every instant is proportional to the *rate* at which the lines of force are cut, it is only necessary, in order to decide this question, to ascertain whether the rate of cutting is, under the circumstances, also uniform. A little reflection will show that just when the rectangle begins to move from its position in fig. 138 it is *cutting* hardly any lines at all, but that its horizontal limbs, like the vertical limbs, are rather sliding along or slipping through them, and therefore at the beginning of the movement the rate of cutting, and consequently the E.M.F., is comparatively low. But when the rectangle has turned through about 90°, it is cutting the lines almost at right angles; there is practically no sliding whatever, and the rate of cutting, and therefore also the E.M.F. produced, is much greater—it is, in fact, at its maximum. This gradually decreases as the rotation is continued until, when near the 180°, the E.M.F. is again at a minimum and the reversal takes place.

FIG. 141



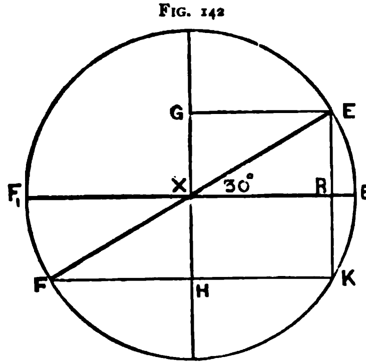
A reference to fig. 141 will make this clearer. A B represents the coil viewed end on in the vertical position; X the axis of rotation, and A_1 B_1 the position of the coil after it has been turned through an angle of 30°. Clearly the number of lines cut by the top limb of the coil are those enclosed in the space A C, and by the bottom limb those in the equal space B D. Therefore the total number cut during this movement of the coil through an angle of 30° from zero may be represented by the sum of these two lines A C + B D.

Now, in fig. 142 E F represents the position of the coil after it has been turned through 60°; if from this point it rotates through another 30° its position is then represented by E_1 F_1, and the lines of force cut during this last movement embrace all those included

in the space E K. Now E K is considerably greater than A C + B D (fig. 141), and therefore, as the field is uniform, the coil cuts a much greater number of lines of force by moving through 30° when its plane is nearly parallel to the direction of the lines, than it does by moving through an equal angle while it is nearly perpendicular to them. But as the speed of rotation is uniform, it takes precisely the same time to pass through these equal angles, therefore the rate of cutting, and consequently the E.M.F., must be much greater in the former than in the latter case. In fact, the rate at any moment is proportional to the *sine* of the angle through which the coil has then moved from the vertical position.

We may look at the matter in a different way: If we have a wire conveying a current, we know that the lines of force will be, in general, concentric circles about the axis of the wire, and the direction of these lines of force and the direction of the current will bear the same relation to one another as the direction of rotation of a right-handed screw bears to its backward or forward axial motion (see p. 87). Further, it has been stated that the induced current flowing in a conductor is always in such a direction as to oppose the action which produces it. Now referring to fig. 138, the lines of force are from left to right through the plane of the coil, and the coil moves in such a way that the number of lines embraced by it diminishes; therefore a current must flow round the coil in a direction such that it tends to keep the number of lines of force embraced by the coil constant, as shown in fig. 138.

FIG. 142



We have defined a magnetic field of unit strength to be one having one C.G.S. line of force per square centimetre, and if a conductor one centimetre in length is moved transversely through this field at a velocity of one centimetre per second, it will cut one line of force per second, and thereby develop one C.G.S. unit of

electro-motive force. If the strength of field, or the velocity, or the length of wire be doubled, the resulting E.M.F. will be doubled, the number of lines cut per second being increased twofold. In fact, if any one of these three quantities be raised, the resulting E.M.F. will be correspondingly increased.

If, however, we simply know the number of lines of force cut per second, the E.M.F. can be calculated without any consideration as to the length of conductor or as to strength of field. If the field is not uniform, or if the wire moves at a varying speed, the rate of cutting, and therefore the E.M.F., will fluctuate. But the *average* of this fluctuating E.M.F. will be equal to the average rate of cutting: that is to say, it can be found by dividing the whole number of lines cut by a conductor by the time in seconds occupied in the cutting. If, therefore, the rectangle in fig. 138 makes one revolution per second, and the maximum number of lines of force embraced by it in the zero position is denoted by N, then each limb will cut 2 N lines per second, because it cuts every line during the downward sweep, and again during the upward movement. Consequently each limb develops an average E.M.F. of 2 N C.G.S. units, and as both limbs are connected in series the total E.M.F. becomes 4 N units. Further, if the rectangle makes n revolutions per second instead of only one, then n times as many lines will be cut per second, and the average E.M.F. will be 4 N n units. But since the C.G.S. unit of electromotive force is so very small, a much greater practical unit, called the volt, equal to 100,000,000 C.G.S. units, is employed for practical work, as was pointed out on page 54. That is to say, an E.M.F. of 1 volt is induced in a conductor which cuts 100,000,000 C.G.S. lines in one second. All results obtained in C.G.S. measure must, therefore, be divided by this number to give the value in volts, and the simple equation may be written,

$$\text{average E.M.F.} = \frac{4\,\mathrm{N}\,n}{100{,}000{,}000} \text{ volts.}$$

It may be mentioned that the value of N is, in actual machines, very high, being, as a rule, several millions.

In practice, it is this average E.M.F. which in such a case concerns us most; but we may observe that if the rectangle were

rotated at a constant speed in a uniform field, the actual E.M.F. being developed at any moment when it had moved through an angle a from the zero position would be

$$E = \frac{2 \pi N n \sin a}{100,000,000} \text{ volts.}$$

This equation refers to the case of two active wires, forming limbs of a rectangle and joined up in series in a manner such as that illustrated in fig. 138 when the E.M.F. of one is added to that of the other. The resulting E.M.F. is, as we have already seen, twice that developed by one active limb; but if the wire were wound in a number of convolutions, it would be necessary to multiply by the number of active limbs then joined in series (instead of by 2, as in the present case) to obtain the total E.M.F.

The function above referred to as the 'sine' is one with which the student will frequently come in contact. Perhaps, therefore, it will now be as well to explain briefly what is meant by the sine of an angle. If in one of the two straight lines which contain any angle, such as E X R in fig. 142, any point, say E, is taken, and from it a line E R is drawn perpendicular to the other line, a right-angled triangle, E X R, is formed. The length of the perpendicular E R divided by the length of the hypotenuse E X, that is $\frac{E R}{E X}$, is a definite numerical value, no matter what the area ot the right-angled triangle may be, provided only that the angle E X R is unaltered. And this ratio $\frac{E R}{E X}$ is called the sine of the angle E X R. The sine of any other angle is similarly measured; for instance, in fig. 141 $\frac{A_1 P}{A_1 X}$ is the sine of the angle A_1 X P. Again in the same figure, $\frac{A_1 C}{A_1 X}$ is the sine of the angle A_1 X C, and in fig. 142 $\frac{E G}{E X}$ is the sine of the angle E X G. If we always choose the same length of line for the denominator, as will be the case if it forms the radius of the same or equal circles, as E X and A_1 X, and consider it to be equal to unity, then the sine is simply measured by the numerator E R or A_1 P—that is, by the length

of the perpendicular. When the angle becomes very small, the perpendicular, and therefore the value of the sine also, becomes very small; in the case of the imaginary angle 0° the perpendicular disappears, and the sine of 0° is therefore 0. When the angle is 90° the perpendicular coincides with and is equal to the radius. The sine of 90° is therefore 1, and this is the highest possible value of the sine. It decreases as the angle further increases, until at 180° its value is again 0. From here it is reckoned as negative, the sine of 270° being -1. By referring to a table such as that on page 104 the value of the sine of any angle can be readily found, and we can, therefore, calculate the relative value of the E.M.F. at any position of the rectangle, and also show diagrammatically how the E.M.F. should rise and fall in a perfectly uniform field.

In fig. 143 the portion A F of the horizontal line A B represents a circle straightened out, each of the four equal parts into which it (A F) is divided being equivalent to 90°—that is, a quarter of a revolution of the rectangular coil. Similarly, this line A F might be subdivided into 360 parts to represent the 360 degrees, and any point along it could then be taken to denote the position of the rectangle when turned through a corresponding angle from zero. Now, we have observed that the E.M.F. at any point is proportional to the sine of the angle through which the coil has then turned from zero; and it is convenient to take a number of points along this line, and at each of them erect a perpendicular proportional in length to the sine of the angle which that particular point represents. During that half of the revolution in which the sines are reckoned as minus—that is to say, from 180° to 360°—the perpendiculars should be drawn below the line, indicating the reverse direction of the E.M.F. and current. For instance, at 90° the sine will have the greatest value, viz. unity, while at 45° the perpendicular will be only 0·707 of that at 90°, because the sine of 45° is 0·707; at 270° the sine is -1, and therefore the perpendicular equal in length to unity is drawn below the line.

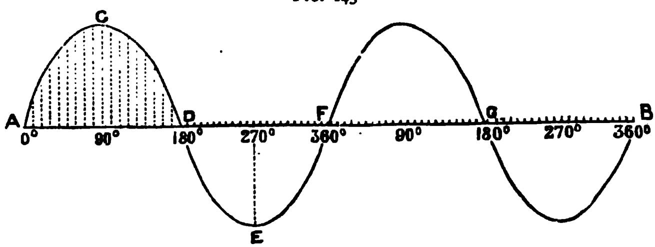
By joining the extremities of these perpendiculars we obtain a curve A C D E F known as a sine curve, which at a glance indicates the manner in which the E.M.F. rises and falls during one complete revolution of a simple coil; and the whole of the curve

from A to B shows the fluctuation of the E.M.F. during two revolutions.

If in fig. 142 E X is taken as unity, it may represent the height of C or E, the highest points on the sine curve, and then E G will be the length of the perpendicular representing the electro-motive force at 60°, for E G is the sine of the angle E X G, which is the angle (60°) through which the coil has turned from the vertical position. Similarly, A_1 C (fig. 141) will represent the E.M.F. developed when the coil has turned through 30°, for A_1 C is the sine of that angle.

The curve (fig. 143) shows that the E.M.F. at 90° is equal to that at 270°, but that it is opposite in direction—that is to say, it is positive in the one case and negative in the other.

FIG. 143

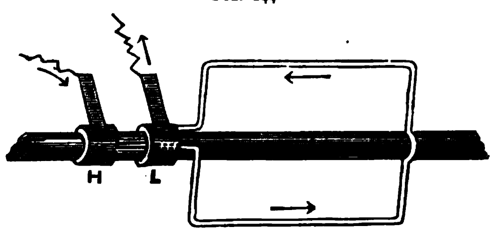


Referring again to figs. 141 and 142, we observe that the 'effective area' of the coil, with respect to the lines of force which it embraces in the position A_1 B_1, is proportional to A_1 L and in the position E F it is proportional to E K—that is, A_1 L and E K are respectively proportional to the number of lines of force passing through the coil in the two positions. Now, $\frac{A_1 L}{A_1 B_1}$ is the cosine of the angle through which the coil has already rotated (for the angles A_1 X A and P A_1 X are equal), or again it is the sine of the angle which the coil makes with the direction of the lines of force; as is also $\frac{E K}{E F}$. Taking, for simplicity, the equal lengths A_1 B_1 and E F as unity, we see that the number of lines of force passing through the coil in any position in a uniform field is proportional to the

cosine of the angle through which it has been turned from its position at right angles to those lines, and also to the sine of the angle which it makes with the lines of force.

Currents which rise and fall in strength and change in direction in the manner indicated by the curve in fig. 143 are known as alternating currents, and a complete cycle as represented by the curve A C D E F is referred to as an alternation. For example, when the rate of alternation of a current is said to be 100 per second, it must be understood that the current rises from zero to a positive maximun, falls to zero again, and reaches a negative maximum, and again returns to zero, 100 times per second. As, however, the term 'rate of alternation' is somewhat cubersome, the words 'periodicity' and 'frequency' have been generally substituted for it.

FIG. 144



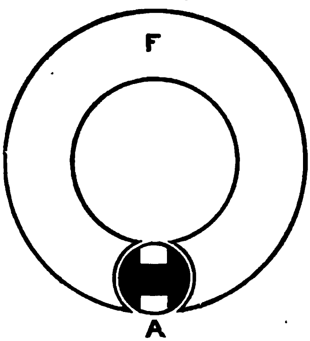
If, however, a rectangle or coil closed upon itself similarly to that shown in fig. 138 were employed, no useful work could be done, as the currents generated would simply circulate round the rectangle and be wasted in heating it. In practice we require to add to the rectangle some device which will enable us to lead the currents away to an external circuit and there make use of them. The rectangle might, for this purpose, be mounted on a wooden spindle (fig. 144) and its ends connected to two flat metal rings, H L, fixed a little distance apart on the spindle, contact being then made by means of a flat spring or a wire brush, pressing against each of the rings. On rotating the spindle or shaft, the rectangle and rings would turn with it, and with a moderate amount of pressure the brushes would make good electrical contact with the rings, the surfaces being kept clean by the rubbing. The contact

brushes being fixed in position, it is easy to attach wires to them, and thus conduct the currents away to any desired point.

It remains now to show to what extent in practice we can comply with the conditions which theory teaches us should be followed if we wish to obtain a high electro-motive force. In the first place, we must make the value of N high—that is to say, the number of lines of force embraced and cut by the coil should be as great as the circumstances will permit. For a very small machine, permanent magnets may be used to supply the field, and for this purpose a horseshoe magnet is found to be very convenient, but it should be bored out, or fitted with soft-iron cheeks of such a shape that there is just sufficient room for the wire coil to rotate between them. The steel should be strongly magnetised, and, if of considerable size, it should be laminated, or built up of a number of thin magnets with their like poles adjacent (see p. 275). A circular magnet (fig. 145), divided at one part of the circle, and with just sufficient space bored out for the coil to rotate, is somewhat better than one of the ordinary horseshoe pattern, although not so easy to make. . Having obtained the magnetic field, the next thing is to get as many as possible of the lines of force to pass through the coils of wire. Iron here comes to our assistance once more, for by winding the rectangle round a core of pure soft iron, we concentrate those lines which would otherwise stray, and the number passing through and embraced by the rectangle is greatly increased. It is almost superfluous to add that the actual area of the rectangle should be as great as practicable, provided that it is kept within the limits of the field, and since, as we have seen, the induced E.M.F. is proportional to the number of active conductors joined in series, the wire may with advantage be wound into a coil consisting of a number of turns instead of only one. Any coil of wire in which currents are induced by its movement within a magnetic field is generally called an 'armature,' and the iron round which the wire is coiled is known as the 'armature core.' The core of one of the earliest forms of armature is shown in section at A, between the poles of the circular magnet F, in fig. 145, and although, when criticised in the light of our present knowledge, the design proves to be very faulty, it will serve sufficiently well to illustrate the principle. The armature

in this case consists of a considerable length of silk- or cotton-covered copper wire wound in the grooves of the shuttle-shaped piece of soft iron, A, which is usually about twice as long as its greatest width. It is provided at one end with a driving-pulley, and at the other end with a device, similar to that shown in fig. 144, for communicating the current to the external circuit. It will be seen that whenever the armature arrives at the position shown in the figure the magnetic circuit is a fairly good one, the air-gaps between the pole-faces of the permanent magnet and the surface of the core not being very great, and the coil wound in the grooves of the shuttle will embrace a considerable proportion of the lines of force produced by the magnet. Good effects can therefore be obtained by rotating such an armature if the magnet employed is a powerful one. The speed of rotation must be high, but this can readily be obtained by any mechanical multiplying device, such as a pulley of large diameter driving a smaller one on the armature spindle.

FIG. 145



It was pointed out when dealing with primary batteries (see p. 81), that an important distinction was drawn between the E.M.F. developed by the battery, and the potential difference available at its terminals, when a current was flowing. In precisely the same way, a distinction must be made between the E.M.F. generated by a dynamo electric machine, and the pressure or potential difference available at its terminals. When the armature is rotated an E.M.F. is developed, and when the resistance of the circuit is infinitely high—when, that is to say, the terminals are left disconnected so that no current can flow—the potential difference at the terminals is equal to the E.M.F. developed. This E.M.F. can then be measured by one of the electrostatic voltmeters described in Chapter VI., or if an electro-magnetic voltmeter of very high resistance be joined across the terminals the current which will pass through the instrument will be so

small that the fall of potential in the armature will be but fractional, and the indication on the voltmeter will therefore be approximately equal to the E.M.F. set up. When, however, an external circuit of relatively low resistance is connected to the terminals, a current of appreciable strength will flow through it, and, of course, through the armature. In such circumstances there will be a fall of potential in the external circuit, which in the absence of any self-induction effects will be equal to the resistance of that circuit multiplied by the current flowing, or if C represents the current, and r the external resistance, the fall of potential V will be $V = C\,r$. If at the same time one of the voltmeters above referred to be joined to the terminals of the machine its indication will correspond to this fall or difference of potential V, and the difference between V and the E.M.F. previously indicated is a measure of the fall of potential in the armature itself (the 'reaction' of the armature field on the main field being neglected). It will also be remembered that although we increased the E.M.F. of a battery by increasing the number of cells joined up in series, there was not a corresponding increase in the available potential difference, unless the external resistance happened to be relatively very high. Similarly with the dynamo armature, although we increase the E.M.F. developed by increasing the number of turns of wire, we do not get a corresponding increase in the potential difference at the terminals. As a matter of fact, it is found that, with an armature of the type under consideration, the increase is not by any means proportional, especially when the speed of rotation becomes very high. One important reason, apart altogether from the internal fall of potential due to the resistance of the armature, consequent upon the increased number of turns, is that the conditions are very favourable for the self-induction of the armature to make itself evident. We have already seen that this effect becomes very marked with rapidly varying or alternating currents, and since, also, it increases with the square of the number of turns of wire, it is obvious that the number cannot be indefinitely increased with any prospect of satisfactory results. The increase of resistance, though not in itself such an important matter, also limits the length of the wire. It is, therefore, preferable to

endeavour to increase the strength and area of the field, and the length of the active limbs of the coil, rather than the number of turns.

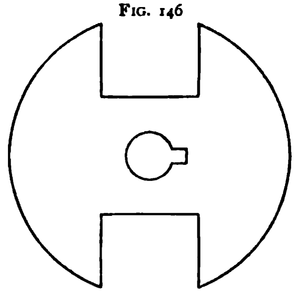
That the design of the shuttle armature is faulty may easily be proved, for, after being rotated for a little time, the iron shuttle or core gets quite warm, even though the armature coil may be disconnected or removed entirely. Now, this heat, so developed, represents a definite fraction of the energy expended in rotating the armature, which, as it does not reappear as electricity available for use, is to all intents and purposes wasted. It is an interesting fact that whenever a mass of metal is rapidly rotated in a magnetic field its temperature rises, the heat being the direct result of currents of electricity which are induced in the metal, and which are known as 'eddy' or Foucault currents. Their initial direction is at right angles to the lines of force of the magnetic field, and also at right angles to the direction in which the mass moves; therefore, in the shuttle armature, they travel lengthways along the iron core, completing their circuit in a more or less circular path in the iron, whence they obtain the name of 'eddy' currents. Moreover they follow the general law in reacting upon the field in which they are produced, in such a manner as to tend to stop the motion of the moving body, that is to say, the armature itself; and in order to overcome this reaction it is necessary to expend a considerable amount of additional power in turning the armature. As a rule, the E.M.F. of these currents is not high, but as the mass of the metal is great, and its resistance therefore small, the currents are sufficiently strong to considerably raise the temperature of the metal. In fact, it is possible to melt a piece of a metal which fuses at a low temperature, by simply spinning it rapidly in a very strong field.

It is evident that such a certain sign as this, that energy is being wasted, must not be ignored, and, since we cannot stop the tendency for the currents to be produced, the only alternative is to put difficulties in the way of their production.

In the case in question, the best method is to 'laminate' the armature, or to build it up with a number of thin discs cut or stamped out to the required shape and bolted together, instead of using a solid piece of iron. One such stamping is illustrated in

fig. 146. The iron of the armature core must be continuous in the direction in which the lines of force developed by the field-magnets have to pass through it, otherwise the efficacy of its action in concentrating these lines would be seriously impaired ; while it must be discontinuous in the direction in which the eddy currents tend to flow, viz. at right angles to the lines of force. To meet these requirements the discs threaded on the spindle must be well insulated one from another, although on account of the low E.M.F., a sheet of thin paper, a layer of varnish, or even the oxide on the surface of the laminations themselves, is, as a rule, sufficient. It is perhaps hardly necessary to adopt this precaution in the kind of machine we have been considering, which is very small, and only made to be driven by hand-power, but it becomes absolutely necessary, as well as economical, in the larger machines driven by steam-power.

FIG. 146



At first sight it would appear, remembering that the E.M.F. developed in the armature coil varies as the rate at which the lines of force are cut, that the potential difference at the terminals of a magneto-electric machine delivering current to an external circuit of constant resistance, should be simply proportional to the speed of rotation, the strength of the field being invariable. But, as we have already indicated, there are several causes which tend to prevent the increase of the potential difference developed by the augmentation of speed from attaining this proportion, the principal being the self-induction of the armature and the electromagnetic reaction of the current in the armature upon the field produced by the field-magnets. It is important to notice that when a current is flowing round the armature coil, the whole armature is in reality an electro magnet, and it acts as such upon the poles of the permanent horseshoe magnet which supplies the field, this reaction, as in every similar case, tending to stop the motion of the armature. In fact, were it not for this reaction, it would cost no more to drive a machine

when it is developing a strong current than when the current is comparatively small. The work done in driving the armature consists chiefly in overcoming the mutual attraction between the armature and the field-magnets. The nature of this may be seen by referring to fig. 138. The direction of the current in the coil is such that, supposing the wire to be wound over an iron core, a south pole would be developed at the end of the core nearest to the north pole of the field-magnet, while a north pole would be developed at the end near the south pole of the field-magnet. Obviously the result of the attraction would be an effort to prevent or resist rotation, and as the attraction increases with every increase in the armature current, it follows that the power required to turn the armature must also be correspondingly increased. When, however, the armature is forcibly rotated against this tendency, the magnetic field is distorted somewhat out of its true position, and, as the current in the armature rapidly alternates from zero to a maximum, this distorting effect will also vary considerably, with the result that the field will be kept in a state of oscillation and its uniformity destroyed. The maximum current in the armature becomes higher as the speed is increased if the external resistance is constant, and the distortion of the field is then greater, the result being a tendency to prevent the terminal pressure rising in proportion to the speed.

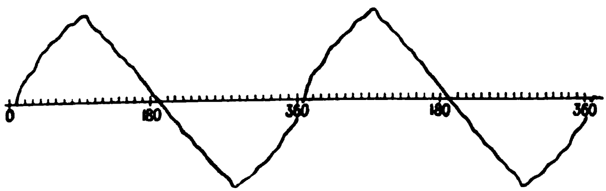
The effect of the self-induction of the armature, which becomes more strongly marked as the speed increases, is to retard the rise and fall of the current. In fact, were we able to plot a curve showing the rise and fall of a current in this shuttle armature, we should find it somewhat similar to that given in fig. 143, for the rise and fall of the electro-motive force, but with the important difference that it would be shifted more or less to the right, its maxima and minima being, however, less in value, as well as occurring later than would be the case if the armature had little or no self-induction. Owing to the fact that it is not possible to construct a practical armature with as little self-induction as the single rectangle, or to make its active limbs cut the lines of force of a uniform field in such a regular manner as is done by our experimental rectangle, we do not in practice obtain a perfect sine curve for the E.M.F. curve of any armature, but only an approxi-

mation thereto, such as that shown in fig. 147. The approximation is, however, a very close one in the case of some machines in which the field is very powerful and in which no iron core is used in the armature. This is also true in the case of certain machines with iron cores, but having the pole-faces shaped to a particular form, instead of being circular.

We shall presently be better able to consider the reaction on the field in connection with a different type of armature, but we may here remark that it is one of the most important points to be borne in mind in deciding how a more powerful and efficient machine can be obtained.

It can readily be imagined that in all the early efforts to construct a dynamo-electric machine, the field was obtained by means of permanent magnets. Machines in which steel magnets

FIG. 147



are employed for producing the field are often called magneto-electric machines, and are sometimes regarded as a class altogether distinct from machines in which the field is developed by one or more electro-magnets, but such a distinction is somewhat arbitrary.

One of the earliest as well as one of the most interesting of the so-called magneto-machines is that of De Meritens, which is still employed for lighthouse purposes. A general view of one form of this machine is shown in fig. 148. It will be observed that fundamentally it is similar in principle to the simple elementary machine which we have just discussed—that is to say, currents are generated by rotating coils of wire in such a manner that they cut lines of force due to permanent steel magnets, but there is a considerable difference as regards detail. For example, a number of steel magnets instead of one only are employed,

with a corresponding number of coils, and the coils glide past the poles of all the magnets in turn, instead of each coil rotating in the field set up by one particular magnet.

The armature in fact consists of a series of sixteen coils fixed round the periphery of a wheel of brass or other non-magnetic material. The method of constructing and fixing the coils is shown in fig. 149, one coil and a portion of the rim of the wheel

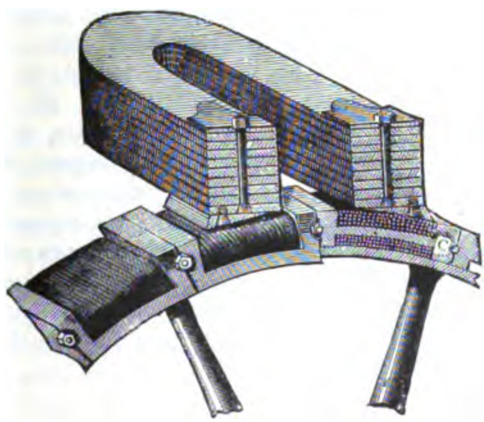
FIG. 148

being in section. A flat core of soft iron C (composed of eighty pieces of soft sheet iron 1 millimetre thick and stamped out to shape) is provided with rather large pole-pieces, and has wound over it about $1\frac{1}{2}$ pound of insulated copper wire. Each coil is distinct from the others, the cores of two adjacent coils being magnetically insulated (as at X Y, fig. 150) by a thin strip of copper. The ends of the pole-pieces of the cores are provided

with semi-cylindrical grooves of the necessary dimensions, so that the whole are firmly fastened together by bolts. It is important to notice that the extensions of the cores reduce the air-space between the poles of the permanent magnets and the cores to a minimum, and therefore conduce to the projection of the greatest possible number of lines of force through the coils, and consequently to the generation of the maximum attainable E.M.F.

The field is produced by a series of eight compound or laminated steel magnets placed horizontally round the armature ring, and fixed to a brass framework. The inner surfaces of

FIG. 149



the magnet poles are provided with small soft-iron pole-pieces, which further reduce the air-gaps between the magnets and the armature cores. The magnets are disposed uniformly round the ring, the coils passing, therefore, north and south poles alternately.

The distance between the limbs of each magnet being exactly equal to that between the opposite poles of the adjacent magnets, and this distance being also equal to the length of each coil, it follows that, on the armature being rotated, each coil passes sixteen alternate poles in one revolution. The manner in which the currents are induced can best be appreciated by a reference to fig. 150, where the ring has only four coils which rotate between

a similar number of magnet poles, N S N S, one coil or segment, A B, being shown in section. When the coils are in the position shown, the minimum number of lines of force is at that moment passing through them, and the E.M.F. reaches its highest value. After traversing another 45° the core-extensions will be opposite the field-magnet poles, and each core will therefore be in the best position to complete the magnetic circuit between two opposite poles, and consequently the coils will then embrace the maximum number of lines of force; at this latter point the reversal of the current takes place. The coils being all wound in the same direction and all connected together in series, it is evident that at any instant the current in the adjacent coils on either side will be opposite in direction to that taken by the current in A B, as they are passing through fields developed by the south poles. Were the adjacent ends of the neighbouring coils connected together, the electro-motive forces in the various coils would therefore neutralise each other, and no current could be urged through the external

FIG. 150

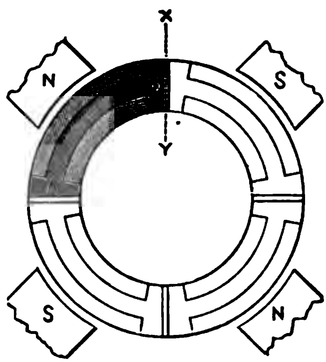
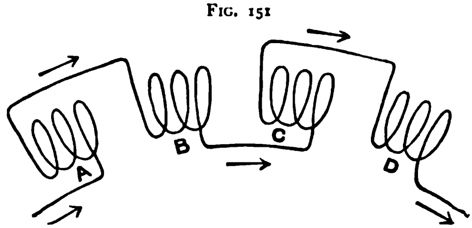


FIG. 151



circuit. This difficulty, however, can be readily obviated, as will be made evident by a reference to fig. 151. Instead of connecting the adjacent ends of two coils together, the connection is made between their two similar ends—that is to say, the end of the coil A to the left hand is connected to the similar end of B, while the

end of B to the right hand is connected to the right-hand end of C, and so on. In this way, although at any moment the currents in adjacent coils are generated in opposite directions, they, instead of neutralising one another, are made to take one common direction through the circuit. This does not, of course, alter the fact that the current delivered by the dynamo is an alternating one—that is to say, as the coils advance from one set of magnet poles to the next, the direction of the current in the whole of the coils is reversed, and therefore also the direction of the current in the external circuit. The whole of the coils in fig. 148 being joined together in series, the total E.M.F. developed is sixteen times that developed in one of the coils, and further the current will alternate in direction at a rate greater by eight times than would be the case if only one magnet were employed and the armature were rotated at the same speed.

It has been pointed out that the best means available for increasing the E.M.F., and therefore also the strength of the current yielded by a machine, is to increase the strength of the field. Now there is a limit, which is soon reached, to the field attainable with permanent steel magnets even if built up of thin sections, because the maximum number of lines of force which can be urged through steel is comparatively low, and even then only a portion of this number can be permanently retained; whereas with good soft iron a far greater number can be forced through, and if the lines of force are produced by a current circulating in a coil of wire enveloping the iron, the question of retentivity does not arise. Consequently, to develop a given amount of power, a machine in which the field is produced by electro-magnets is considerably smaller than one in which steel magnets are employed.

Primary batteries might be, and in fact were at one time, used to furnish the current for the purpose of exciting the field-magnets, but it is far more economical and advantageous to obtain this current by means of secondary cells, or of a small dynamo. In many cases, more particularly with the large machines of modern design, a relatively small dynamo is attached to the shaft of the machine which it has to excite, as illustrated in fig. 165. This auxiliary machine, which we will for the present refer to as the exciter, must be able to excite itself—that is to say, it must be able to

supply the requisite current for its own field-magnet coils—and to yield a current continuous in direction. Descriptions of several such dynamos will be found in the following chapters. It must be remembered, however, that the power necessary to excite the magnets is in all cases to be regarded as so much loss.

Let us now return to fig. 138 in which we have a single turn or coil of wire revolving in a field of force, and suppose that, instead of a single coil, we have two coils rotating about a common axis, but that the planes of the two coils are inclined at an angle of 90° to one another—that is to say, they are at right angles. It is evident, if these coils are electrically independent of one another, that the E.M.F. developed in each coil will be represented by a curve or wave exactly similar to that given in fig. 143, but that one curve will be 90° in front of the other—that is to say, at the instant when the E.M.F in one coil reaches a maximum value, the E.M.F. in the other will be zero. The ends of the two coils may be brought out and connected to four contact or 'slip' rings after the manner indicated for one coil in fig. 144. The four slip rings being insulated from one another, it follows that the circuits through the two coils are quite separate and distinct. Another method of connection is to join one end of each coil to a common slip ring, the other ends being connected each to a separate ring. Three rings only are actually required in the latter case, in which the circuits of the two coils are not independent, and it is important that the effect of this arrangement should be carefully studied. In the first place, the E.M.F. of the individual coils—that is to say, the E.M.F. set up between the respective free ends and the common end or junction—will remain unaltered. In other words, the E.M.F. of one coil will not be affected by connecting to one end of it another coil with another, and possibly different, E.M.F. The potential difference between the two free ends will, however, have a definite value in any particular position of the coils as they rotate in the field of force. We will, for the sake of clearness, call the potential of the junction or common end X, and the potential of the free end of one coil F, the potential of the free end of the other coil being indicated by F′; all these potentials being referred to the earth as zero potential. Obviously the potential difference between the free end of the first coil and the

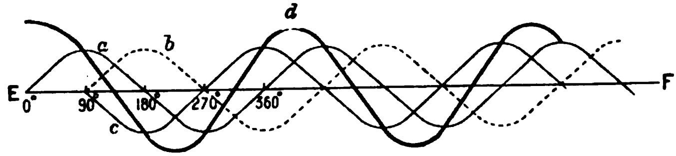
common end will be $F - X$, while the potential difference between the free end of the other coil and the common end will be $F' - X$. From this it will be seen that the potential difference between the free ends of the two coils is

$$(F - X) - (F' - X) = F - F'.$$

Hence, in order to ascertain the wave or curve of the potential difference between the two free ends of the coils, we simply subtract from one another the instantaneous values given by the waves of E.M.F. for the two coils, or, in other words, reverse the sign of the values given by one wave and add these values to those given by the other. A reference to fig. 152 will perhaps serve to simplify the matter.

The waves *a* and *b* give the E.M.F. induced in each coil, and it will be noticed that the wave *b* is at every point 90° behind the

FIG. 152

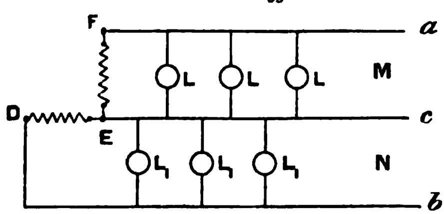


wave *a*. The wave *c* is simply *b* redrawn with its sign reversed at every point, and the wave *d* is obtained by adding the values given by *a* and *c* at every instant. If these various curves are plotted carefully it will be found that the maximum ordinate (or vertical distance from the horizontal or zero line E F) of *d* is exactly $\sqrt{2}$ times the maximum ordinate of *a* or *c*, and further it will be found that if *a* and *b* are sine curves, *d* will be a sine curve also. Thus we arrive at the important result that the maximum E.M.F. induced between the two rings which are connected to the free ends of the coils is exactly $\sqrt{2}$ times the E.M.F. induced between either of these two rings and the third one which forms the common junction of the two coils.

All that has been said in reference to the E.M.F.'s can be similarly applied when considering the currents produced by these E.M.F.'s. We may suppose the two coils to be represented

diagrammatically by F E and D E (fig. 153), where F and D represent the free ends, and E the junction or common end. Between the slip rings to which the armature coil F E is connected is the external circuit M, consisting of a pair of wires or leads F *a* and E *c* and a number of lamps L. Similarly, between the slip rings to which the armature coil D E is connected is the external circuit N, which consists of the wire E *c* above referred to, the wire D *b*, and the lamps L_1. So long as the lamps remain unaltered in number the currents in the two circuits M and N will have the same maximum value, but these maxima will be displaced by 90°. The current in the common lead E *c* can be found by adding the values given by the two waves at any instant, and it will be seen, if this is done, that the maximum current in E *c* will be $\sqrt{2}$ times the maximum current in F *a* or D *b*. It

FIG. 153



follows that if we wish to have the same current density in the line *c* as in *a* or *b* the section of *c* must be $\sqrt{2}$ times larger than that of *a* or *b*.

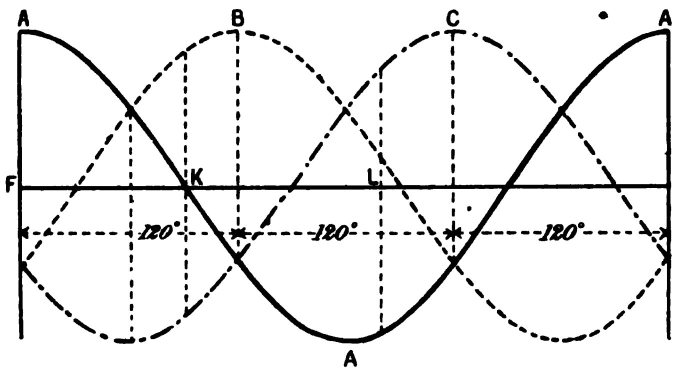
A machine whose armature is wound with coils displaced by 90° as above, is called a two-phase machine, and the currents so produced can be utilised for the important object of obtaining a rotating field, as will be explained later.

If the currents are distributed from four slip rings the system is called a two-phase four-wire system; if the distribution is from three slip rings the system is a two-phase interlinked or three-wire system.

If *three* coils are placed on the spindle *a b* (fig. 138), having their planes inclined at 120° to one another, it is clear that each coil will generate an E.M.F. displaced by 120° relatively to the

other two. Moreover, it will be found, if the three curves of E.M.F. are drawn out as in fig. 154, that at any instant the algebraic sum of the three is zero, or, since what applies to E.M.F.'s applies equally well to currents, it follows that if each coil is provided with separate leads and is 'loaded' with the same number of lamps the algebraic sum of the currents in three of the leads will be zero, and therefore we can connect these three leads together without causing an alteration in the current distribution. Further, if necessary, we can entirely discard the common lead, and, connecting the three ends of the coils together, the lamp leads may be connected between the free ends of the coil as is

FIG. 154



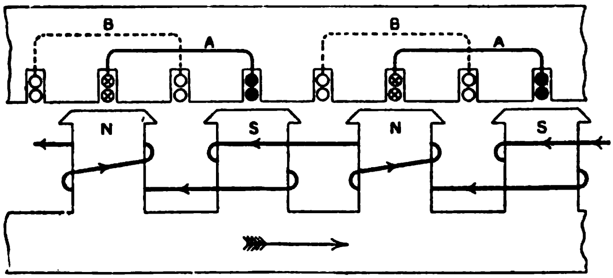
shown in fig. 159, and each coil may be considered as the return of the other two. It must be remembered, however, that the E.M.F. between the free ends of the coils will be $\sqrt{3}$ times as great as the E.M.F. induced in any one coil.

It now remains to be seen how generators can be constructed to develop the requisite currents differing in phase as indicated by the curves in figs. 152 and 154.

The diagrams in figs. 155 and 156 show the arrangements required for a two-phase machine. The field coils are wound so that alternate N and S poles are produced, and the thick, full lines marked A show the armature windings which would be required for a simple single-phase alternator. It will be observed that in

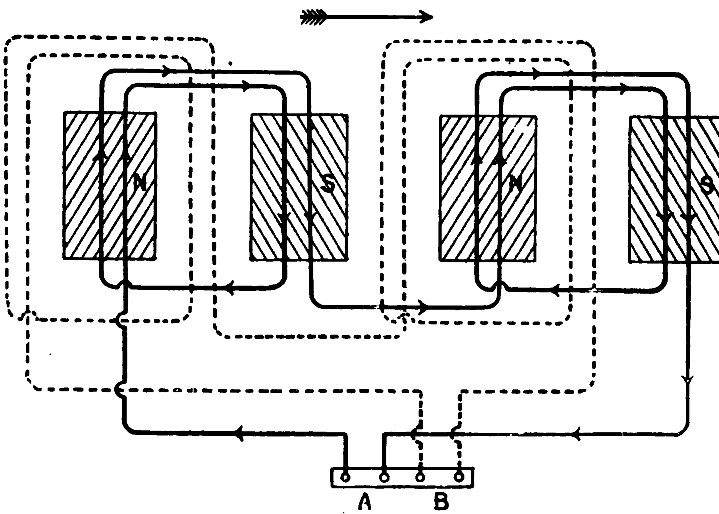
the position shown the E.M.F. in these coils marked A is at its maximum. A second set of coils marked B is shown exactly

FIG. 155



midway between the A coils, and evidently the E.M.F. in the B coils is at its minimum value—that is, at zero.

FIG. 156



It should be noted that in dealing with machines with more than two poles it is convenient to refer to distances on the

armature in electrical, instead of geometrical, degrees—that is to say, the distance between the centres of two neighbouring poles is to be taken as 180 electrical degrees whatever the geometrical distance may be. Thus, in a machine with six poles, the pole pitch will be 60° in geometrical terms, but 180° in electrical terms. In the case of two-pole machines the two terms are identical.

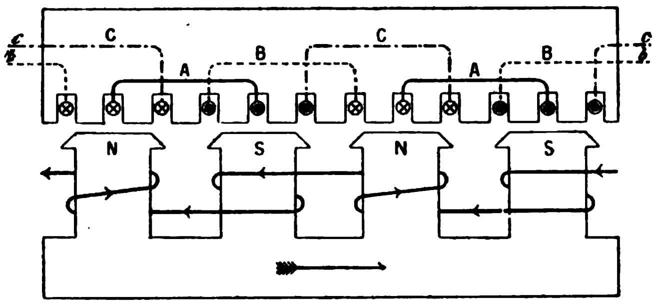
If the A coils in the armature (fig. 155) are all joined in series and connected to one pair of mains, and the B coils likewise joined in series and connected to another pair of mains, we shall have two separate circuits, the E.M.F.'s in which are of the same frequency and value, but which differ in phase by 90°. Fig. 156 is a developed diagram of the winding of a two-phase alternator with two convolutions in each armature coil, and with one coil per pair of poles for each phase. It shows clearly the method of winding and connection to the external circuit, and also the relative position of the A and B coils with respect to the pole-pieces when the current in the A coils is at its maximum, and that in B is zero. Any simple single-phase alternator can readily be converted into a two-phase machine by simply adding a second set of armature coils with the active portion exactly midway between those of the existing set. Subject to the limitations imposed by the permissible rise in temperature the output from a single-phase machine can be largely increased (in some instances almost doubled) by converting it into a two-phase machine, the increase in weight and cost being that due to the second set of coils only.

A three-phase machine can be constructed by employing three sets of armature windings, placed in equidistant slots as shown in fig. 157, the relative space, with respect to the pole-pieces, occupied by any one set, say the A coils, being similar to that in the two-phase or single-phase machines. A corresponding developed diagram is given in fig. 158. In the positions shown the E.M.F. in the A coils is at its maximum; the E.M.F.'s of B and C are equal, and as the field poles are moving to the right, the value of B from this point decreases, and that of C increases. We have already explained that in a three-phase machine the sum of the

three currents at any instant is zero, and that therefore a return wire or wires may be dispensed with.

The diagrams show the way in which one end of each of the three armature coils may be connected to a common junction M,

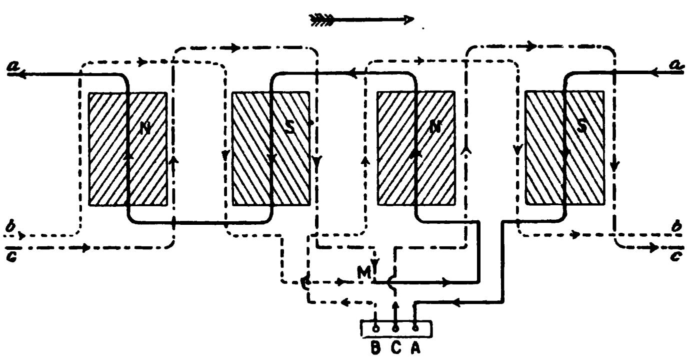
FIG. 157



the other or free ends being led to the terminals B, C, A, and from thence to the external circuit.

These simple connections give what is known as the 'star' method of winding, and fig. 159 shows the armature of the

FIG. 158



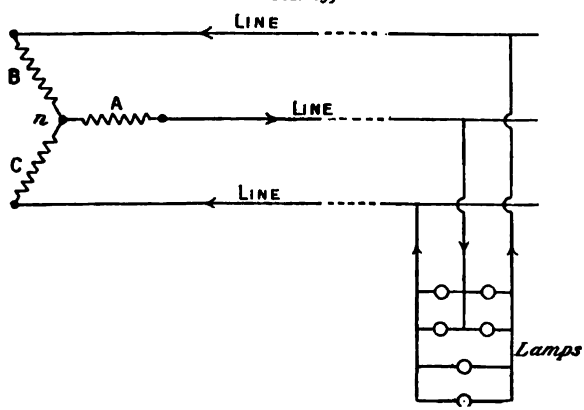
generator and the lamp loads connected by the three main leads. When the current in the A coils is at its maximum, as in the case just considered, then those in the B and C coils are equal

and each half the value of A; at this moment the B and C leads act as a return to A, as indicated by the arrows in the diagram.

The three sets of coils in the armature of the generator are sometimes joined as in fig. 160, and the three junctions connected to the three main leads. This gives us what is known as the 'mesh' grouping or method of winding, as indicated in the figure.

It will be seen that the mesh grouping approximates somewhat to a parallel method of winding, when considered with respect to the external circuit, with the result that the pressure between the mains is less than with the equivalent star grouping, the currents

FIG. 159

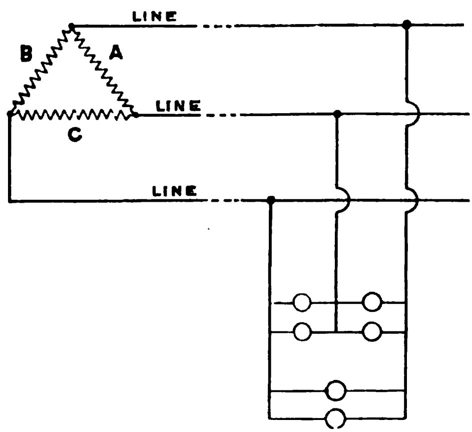


being correspondingly heavier. For transmission of power to great distances, where low current strength and correspondingly high pressure in the mains is essential, the star grouping is preferable. To obtain a given pressure in the mains with a mesh grouping requires about 73 per cent. (that is, $\sqrt{3}$ times) greater length of conductor in the armature than with the star grouping.

There is the advantage in the case of mesh grouping that, although one set of windings may break down, the machines will continue to run as two-phase machines, whereas with star windings the machines would become simple single phase.

Polyphase machines are especially suitable for the transmission of power to considerable distances, where a high pressure on the line is essential to economy. For such work direct-current machines are rarely employed on account of the trouble experienced with the commutators (see Chapter IX.) and the difficulty in maintaining the insulation of the armature windings. The objection to single-phase machines on account of the difficulty in starting the motors will be referred to in Chapter XII. Polyphase machines can also be used with advantage on a low-pressure system where it is necessary to drive electric motors and also feed lamps. The

FIG. 160



method of connecting up the lamps is indicated in the diagram, fig. 159. They may be joined across any one pair of mains, and they should be so arranged that an approximate balance is maintained—that is to say, the loads should as nearly as possible be made uniform.

We have seen in the earlier part of this chapter that the E.M.F. induced in a conductor moving in a magnetic field is proportional to the rate at which it cuts the lines of force. Suppose, for example, we have a conductor of length l centimetres moving in a direction perpendicular to its length at a rate of v centimetres per

second. In one second the conductor will have swept out an area of $v\ l$ square centimetres, and if this area be traversed by a uniform field having a density of $\mathbf{B}$ lines per square centimetre, the number of lines which the conductor will cut in one second will be $\mathbf{B}\ v\ l$—that is to say, the E.M.F. induced will be $\mathbf{B}\ v\ l$ C.G.S. units or

$$\frac{\mathbf{B}\ v\ l}{10^8} \text{ volts.}$$

If the speed is not constant, and if the field also varies from point to point, the above expression for the E.M.F. induced at any instant still holds if $\mathbf{B}$ be the density of the field in which the conductor moves at that instant, and v the speed at which it moves at the same instant.

It is, of course, only the relative speed of the conductor and field which need be considered, and not the actual movement of either, the E.M.F. produced for a given relative speed being the same whether the conductor or the field be stationary.

If we wish then to increase the E.M.F. induced we have three factors which may be varied, viz. the length l of the conductor, the velocity v, and the density $\mathbf{B}$ of the field.

In the practical case of an armature conductor it is obvious that the length may not be increased beyond certain limits, for besides increasing the resistance and self-induction of the armature, the cost of the machine will be too great. The velocity is limited by the mechanical strength to resist the centrifugal forces tending to rupture the armature, and it only remains to be seen how the density of the field can be increased. This last method of increasing the E.M.F. is the freest from objections, and it has the all-important effect that the stronger the fixed field is as compared with that developed by the armature, the less is the reaction and consequent distortion of the field. This question of armature reaction will be more fully dealt with in another chapter.

It is clear that if we reduce the reluctance of the path of the lines of force the number of lines will be increased for a given magnetomotive force, and if the reluctance be reduced, but at the same time the cross-section of the path maintained constant, the density of the field will be increased. Now in an alternator the reluctance

of the magnetic circuit may be made as small as the circumstances usually require by sufficiently reducing the air-gap, the reluctance of the iron parts of the magnetic circuit being in many cases negligibly small. If the coils are wound on a smooth armature core there is, however, a limit to the shortening of the air-gap which is determined by the space taken up by the winding; for the air-gap is, of course, to be reckoned as the distance between the face of the pole-shoe and the face of the armature core, the permeability of the copper conductors being the same as that of air. Moreover, a certain clearance is always necessary in order to allow for a slight eccentricity, or for vibrations which might cause the rotating part to foul. In order then to reduce the air-gap as much as practicable it is now the almost universal practice to have a number of slots equally spaced round the armature periphery, and to wind the coils through these slots, or—which amounts to the same thing—to prepare the coils separately, and then to fix them in the slots. These slots may be either quite open, partially closed, or completely closed.

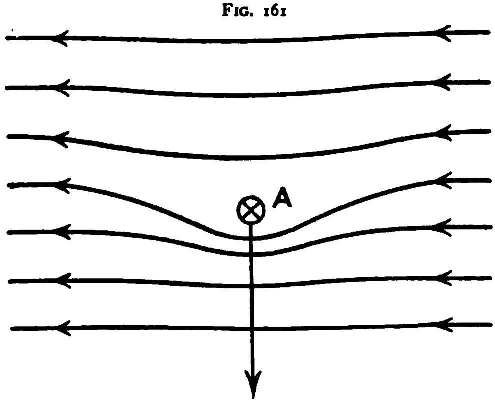
The use of slots has many advantages, such, for instance, as the mechanically excellent manner in which the conductors are held in position and the ease with which the armature may be wound. If the slots are open or partially closed the coils are kept in position by driving wedges in at the top of the slots.

There is another point worthy of notice in connection with the use of slots and to which reference should be made: when a conductor moving in a magnetic field has a current induced in it there is a mutual force exerted between the current and the field tending to stop the motion of the wire, and this force has to be overcome in order to drive the conductor across the lines of force, and the mechanical energy thus expended corresponds to the electrical energy produced. This will be clear from an inspection of fig. 161, in which the conductor A is shown to be moving across the magnetic field, thereby causing a current to flow in a direction perpendicular to the plane of the paper from front to back. As a consequence the field is distorted in such a way that the density in front of the conductor is increased and the motion thereby retarded. When the conductors are placed in slots, however, nearly all the lines of force crowd into the adjacent teeth, and the

'magnetic drag' is transferred from the conductor to the teeth. The insulation of the coils in the slots is thus rendered much less liable to be disturbed or injured, and this is a distinct advantage arising from the use of slots for the conductors.

In modern alternators either the field system or the armature may be made as the rotating part. For large machines giving a high pressure it is usual to have the armature stationary because this arrangement allows the current to be collected from fixed terminals instead of slip rings. This in itself is a great advantage; moreover, it is much easier to maintain an efficient insulation for the armature coils when they are stationary than when they form

FIG. 161



part of the rotating mass. On the other hand, however, the armature, which is the most expensive part of the machine on account of the winding, &c., has smaller dimensions in a machine of equal output in which the armature rotates in a field developed by field magnets which are stationary. As a rule it may be said that small low-pressure machines are, as a matter of practice, made with a rotating armature, while large high-pressure machines are made with a rotating field system.

In fig. 162 the method of construction in a modern three-phase alternator is illustrated. The armature core A, which in this case is the stationary part (or stator), is built up of soft-iron stampings 0·5 mm. thick bolted together into the cast-iron frame B.

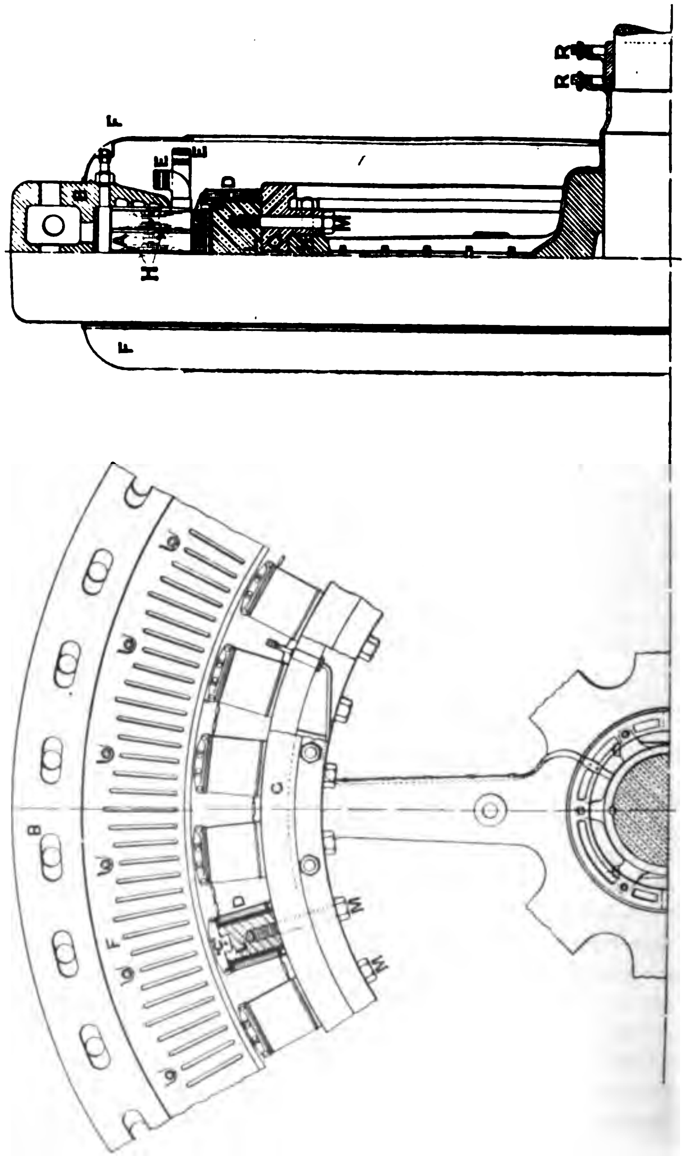


FIG. 162

These stampings have a very high permeability and are insulated from one another by being pasted on one side with paper, or sometimes by being coated with a paste containing chalk. In this way the eddy currents which are induced by the sweeping of the magnetic field across the core are reduced to a minimum.

In machines in which the armature rotates, the laminations are collected and bolted together on what is known as a 'spider,' and the construction of the armature is similar to that used for direct-current machines and described in the following chapters.

It is usual to provide ventilating channels or 'ducts' in the armature core, and this is done by simply dividing the total number of core plates in two or three parts (according to the number of ducts required), and inserting distance pieces between the parts. In the example shown in fig. 162 there are three ventilating ducts in the armature core, as is indicated at H in the sectional view, and the air passing freely through these channels keeps the core cool.

The armature coils are placed in slots stamped in the core laminations A; the cross-section shown in fig. 162 has been taken, however, on a line passing between two slots—that is to say, through a tooth—and therefore only the ends of the coils E E are visible. It is to be noticed that whilst the coils of one phase are wound in a horizontal plane the coils of the other two phases are bent up at right angles at the end, this being done in order to allow the coils to cross without touching. The ends are protected by means of the covers F F which are bolted on to the cast-iron frame B, and which being perforated do not affect the ventilation to any marked degree.

The coils are wound on a former, insulated, and, after being tested, are slipped into position in the slots, the width of each coil being such that whilst one side moves in a field of one polarity the other side moves in a field of the opposite polarity, and thus the E.M.F.'s induced in each side of the coil assist one another so that the total E.M.F. induced at the terminals of a coil is twice that induced in one side. The slots are lined with insulating material of a thickness and nature depending on the E.M.F. which the machine is intended to develop. Presspahn (a composition

of oiled and compressed paper) and oiled tape for low pressures, and in addition mica or mica compositions for high pressures, are the most usual materials for this purpose. If the slots are nearly closed it will often be impossible to use former-wound coils, and in such cases the coils must be wound in position in the slots.

When a coil passes from a position opposite, say, one S pole across the adjacent N pole to a position opposite the next S pole, the E.M.F. induced passes through a complete cycle or alternation; thus, one revolution of the armature indicates that the E.M.F. induced in a coil has passed through the same number of cycles as there are pairs of poles on the machine—each pair of poles corresponding to one cycle. If the machine runs at n revolutions per second the number of cycles per second through which the E.M.F. induced in a coil will oscillate will be $\frac{p\,n}{2}$ where p is the number of poles.

Another term which is often used in this connection, to which we have already referred, and which should be clearly understood, is 'frequency.' The frequency of a machine is defined as the number of complete cycles which the E.M.F. induced in a coil passes through in one second. The sign $\sim$ is usually employed to indicate frequency, so that if an E.M.F. passes through 25 cycles in one second we may say that the frequency is 25 $\sim$. The majority of the machines at present in use work at from 25 to 50 cycles per second, and to obtain the latter a coil on a two-pole machine would have to be driven at 3000 revolutions per minute, a speed which is prohibitive except in the special type of machine which will be described later, and for this reason multipolar machines must be used to produce a practical frequency.

Reverting to fig. 162, it will be remembered that when the power to be developed is considerable it is the practice to make the field system the rotating part of a machine, and the figure illustrates a typical method of construction. A wheel, K, of cast iron forms the frame of the magnet system, and to the rim of this wheel cast-steel rings are bolted as shown at G. These steel rings form the magnetic yoke to which the pole cores L are bolted by means of two screws, one of which is

shown at M, and by simply removing the screws from each pole-core the latter may be removed when necessary with the greatest ease. The pole-cores may be laminated or cast solid, but in the latter case the pole-shoes must be made separately of laminated iron and either dovetailed into the cores or bolted thereon, for it is imperative that the shoes at least be laminated in order to keep the loss due to eddy currents (which, it may be mentioned, the presence of the armature teeth gives rise to) as low as possible. In the design illustrated, the pole-shoes C are made of laminated iron, the cores L being of cast steel. Four bolts and two stiff end-plates enable the laminations to be firmly clamped together, and the figure clearly illustrates the dovetailing of the shoe into the core.

The field coils D are wound on bobbins and slipped on to the cores before they are bolted into position, and it is thus easy to remove any coil for repairs without dismantling the machine. The coils are all connected in series and are joined together so that the poles are alternately N and S, the two ends of the coils being brought down to a pair of slip rings R fixed on the shaft by means of which the exciting current is led in. The excitation is provided by a direct-current machine which is usually mounted on the alternator shaft.

In the early history of the manufacture of dynamo machines each manufacturer had more or less a special and independent design for his machines; but experience has shown that the type described above is, in general features, the most satisfactory, and this type has consequently become standardised.

A few details concerning a three-phase alternator constructed by Messrs. Siemens Brothers for an output of 165 kilowatts will doubtless be of interest.

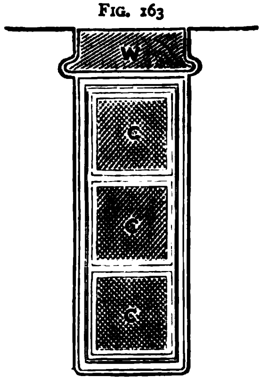
The machine was constructed with a rotating field system, the peripheral speed of the pole-shoes being about 8200 feet per minute. This may be taken as a safe average for the peripheral speed of rotating parts, and it should not be exceeded without exceptional care being taken in the mechanical design.

The bore of the armature is 42″ and there are 96 slots for the reception of the coils. The armature core is built up of laminations 0·5 mm. thick, and one ventilating duct is provided of

$\frac{3}{8}''$ width. The axial length of the armature inclusive of the duct is $7\frac{3}{16}''$. The laminations are pasted on one side with paper 0·05 mm. thick, which is a sufficient amount of insulation to prevent the flow of eddy currents across the laminations. The outside laminations are made thicker and stiffened with brass fingers to prevent them spreading out.

The armature coils are made of stranded copper conductors, each consisting of 37 strands of 1·5 mm. wire braided together to form one conductor. Stranded conductors have the advantage that they are much more flexible than solid ones, and can therefore be more readily bent so as to occupy the required positions. The stranding also has the additional advantage of diminishing the eddy currents which would be produced in a large solid conductor. There are three conductors in a slot, and the winding for each phase is distributed over four slots per pole, instead of all being concentrated in one slot per pole. Thus for the three phases there are twelve slots per pole, and since there are eight poles, this gives a total of 96 slots.

FIG. 163



In building this machine tubes of presspahn were made, and the coils were wound by threading the conductors through these tubes on a former and then slipping tubes and coil into position in the slots. A cross-section of a slot with the conductors is shown in fig. 163.

It will be seen that the whole of the conductors are kept in position by a wooden or fibre wedge W, driven into grooves made for the purpose. The total depth of the slot is 45 mm., and the width is 15 mm. The insulated width of the conductors is 11·3 mm., the bare width 10·5 mm., and the cross-section is square.

The rim, arms and boss of the pole frame are of cast steel, and the pole-cores are also of steel of circular section and bolted direct on to the rim. The pole-shoes are of laminated iron

riveted together and screwed on to the pole-core, and they are shaped so that the E.M.F. wave is approximately a sine curve.

The field coils are wound with bare copper strip of dimensions 4·6 mm. by 2·4 mm., and between each turn there is a layer of paper for insulating purposes. After being wound the coils are turned up in the lathe and coated with varnish. The total weight of copper in the coils is about 470 lb. The maximum exciting current is 30 amperes, and the coils being connected in series, the two terminals are led away to slip rings on the shaft to which the exciting current is applied.

The air-gap is 10 mm. and the current per phase is 204 amperes. The external pressure developed is 550 volts between any two of the three terminals, that is, $\frac{550}{\sqrt{3}}$ or 318 volts per phase between the neutral point and each ring. Since there are eight poles, and the machine runs at 750 revolutions per minute, the frequency is $\frac{750}{60} \times \frac{8}{2} = 50$ cycles per second.

The castings, armature core, &c., are adaptable in every way for a two-phase or single-phase winding.

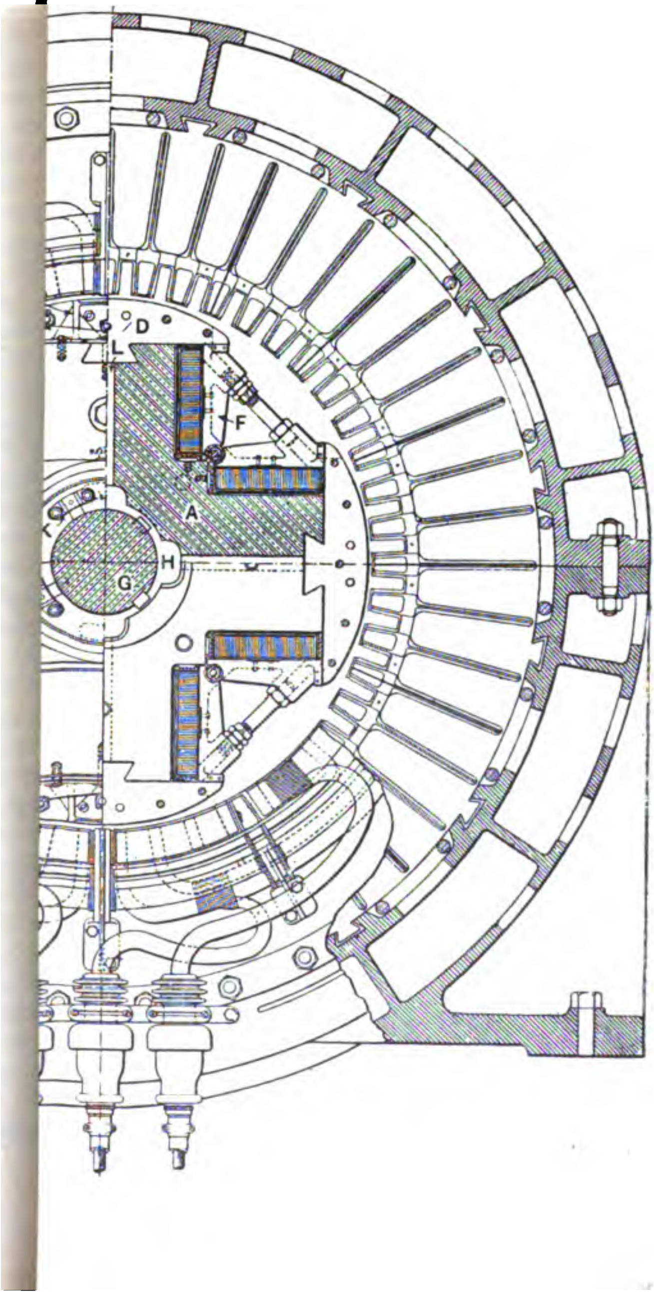
When the machine is wound for single-phase currents, part of the slots are left unwound because the extra pressure obtainable by completely winding the slots for single phase current would be very small in proportion to the increased expenditure of copper. It is usual to wind about two-thirds of the slots of a single-phase machine.

Within the last few years the introduction, in a commercial and highly efficient form, of the steam turbine in place of the reciprocating steam engine has caused a great development in the design of dynamo machines. It will perhaps be understood that the steam turbine is a purely rotary type of engine in which steam by impact upon properly shaped blades gives up its energy to the revolving mass. The feature of this type is that the engine must move at a very high velocity if it is to be efficient, and it is quite common for a steam turbine to run at 3000 revolutions per minute. Clearly, then, if a dynamo is to be coupled direct to a steam turbine the combination must run at a great speed, and therefore extreme care must be taken in designing the rotating

part of the dynamo in order that the centrifugal forces may be successfully withstood, and on this account the rotating part is generally of small diameter but of comparatively great length. We thus have a machine of small dimensions developing a high power with losses proportionately high in consequence of the immense speed, and it will be obvious that if the machine is to remain cool great care must be taken to dissipate the heat corresponding to the losses—that is to say, ventilation must be specially provided for in machines of this class, which are known as turbo-generators or turbo-alternators, the former term being, however, generally restricted to direct-current machines. There is another feature which makes the ventilation in such machines of special importance, viz. the necessity for accurately balancing the rotating parts, *i.e.* the rotor, and for a symmetrical arrangement of the provisions for ventilation. Of course, with even slow-running machines it is necessary to properly balance the structure in order that a uniform E.M.F. may be produced, and to prevent mechanical injury. When, however, we have to deal with high-speed machines much greater precautions are obligatory, because even a little inequality may result in dangerous vibrations, and this want of uniformity in the balance may be caused by an inequality in the cooling of the machine. The temperature at which high-speed machines are worked is higher than in the case of slow-speed machines, and insufficient ventilation can, therefore, be readily imagined as a possible cause of defective balancing. In fact, cases have been known in which a machine which was perfectly balanced at no load became unbalanced at full load. The insulation may also be affected by inequality in the heating of the parts, and many materials which are suitable for low-speed machines are altogether inadequate in turbo-machines.

Perhaps the clearest way of describing the special features of a turbo-alternator will be to take an actual example and to discuss the various points as they present themselves.

In fig. 164 a 3000 kilowatt three-phase turbo-alternator, as built by Messrs. Dick, Kerr & Co., is illustrated in elevation and cross-section. As is always the case with turbo-alternators the field system rotates, for reasons which have already been indicated. We will first examine the field system, which presents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H
G

novel and interesting points of construction. A solid steel casting A, having four long polar projections, is bored out to a larger diameter than the shaft, so that there is an annular space H between the shaft and casting. Two steel cross-pieces B are keyed on the shaft G and hold the casting A in position by means of bolts. The cross-pieces B have four holes as shown at K, which admit the air to the annular space H, and thus there is a clear passage from end to end of the shaft. The polar projections A are drilled radially, as at L, right through to the air chamber H. The pole-shoes are laminated and built up in sections, each section being separated from the neighbouring ones by ventilating ducts which are arranged opposite the radial holes L. Each set of laminations is held together by five bolts, and there are two longitudinal holes in each pole-shoe running parallel to the shaft and which also assist in the ventilation. It will thus be seen that special care has been taken to render the ventilation efficient. Massive brass end-pieces, C, bolted to the laminations keep them from spreading out, distance pieces being, of course, fitted in the ventilating ducts. The laminations are dovetailed into the casting A, and the end-pieces are dovetailed into B, longitudinal movement being prevented by small screws.

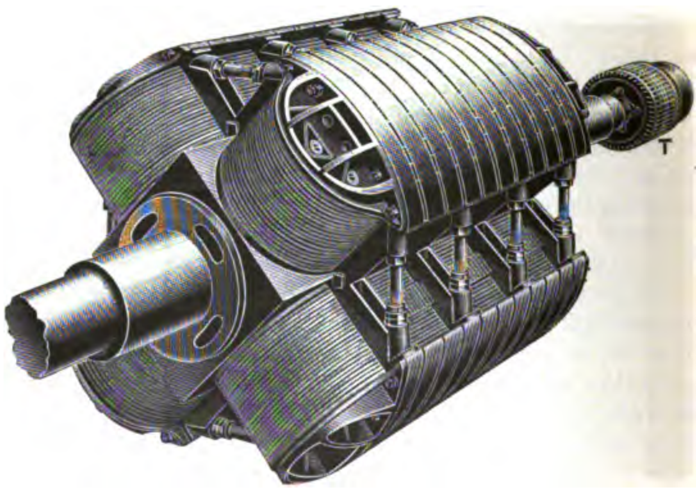
The pole-shoe faces are not concentric with the armature bore, but are struck with a smaller radius in order that the flux distribution on the armature surface may approximate to a sine wave more closely than would be the case if the pole-shoe face were actually concentric with the armature bore. The field coils E are of solid copper strip wound edgewise, and the turns are insulated by means of paper and mica. The coils are supported on special copper bobbins, which are then slipped on to the pole-cores and held in position by the pole-shoes. The brackets F are of interest. These are intended to keep the coils from spreading out as a result of the centrifugal force component in the plane of the coil. The centrifugal force at any part of the coil is, of course, radial, and has components respectively perpendicular and parallel to the plane of the coil; the former component is counteracted by the pressure on the pole-shoe, and the latter by the brackets F.

The completed field system is shown in fig. 165, and an inspection of this will help to make the various points clear.

The small armature T shown at the end of the shaft is the moving part of the direct-current dynamo which provides the current for exciting the field-magnets of the turbo-alternator.

The field coils after being assembled and connected up are coated on the outside surface with a special varnish which is both oil-proof and water-proof. The terminals are brought down to the two collector rings of manganese bronze which are fitted on to the end of the shaft near the exciter, and the connections of the leads to the collector rings are protected by a cap, S (fig. 164), which is easily removable for inspection when necessary.

FIG. 165



The armature core discs are dovetailed into a cast-iron frame as shown in fig. 164, and ventilating ducts are provided opposite those in the pole-shoes. The frame is perforated, and there is thus a free passage for the air from the annular space round the shaft, right through the body of the field system, and thence through the ventilating ducts in the armature core to the outside of the frame.

Massive end-plates, P P (fig. 164), stiffen the ends of the armature core, and by means of the bolts Q the whole are clamped firmly

together, stiffening fingers being placed at regular intervals in the armature core ducts as shown in the transverse section.

The armature winding is distributed in slots stamped in the armature core, and an examination of figs. 164 and 166 (the latter of which illustrates the complete stator) shows that the coils

FIG. 166

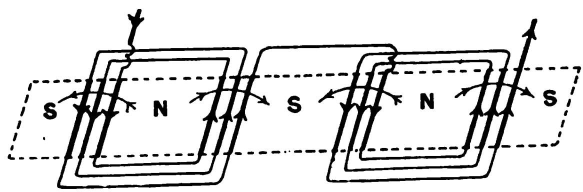
for each phase are wound in four slots per pole—that is to say, there are twelve slots per pole for the three phases, or forty-eight slots in all. The windings are connected in star fashion, and the three terminal conductors are brought through porcelain tubes.

The overhanging ends of the armature coils are supported by the brackets N (fig. 164), which are screwed on to the massive

end-plates P P, the whole being protected by perforated shields which are also held in position by the elongated bolts Q already referred to.

Messrs. Brown, Boveri & Co. make the rotating field system in their turbo-alternators cylindrical, and the field coils are wound in slots in an iron core in a manner similar to that in which armature coils are wound. A diagrammatic sketch of the

FIG. 167



development of such a rotor is given in fig. 167, in which S N &c. represent the polarities developed by the current circulating in the coils, of which the heavy lines represent the straight sections embedded in the slots. For small machines the field core is made in the first place solid, and the longitudinal slots for the reception of the coilsare milled out, not, however,

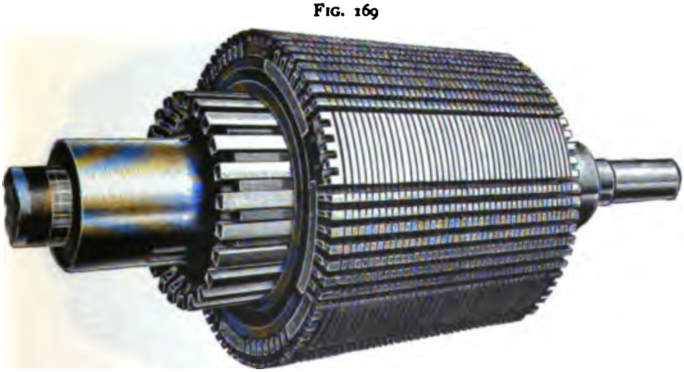
FIG. 168

over the complete circumference of the core, but only in those portions in which the coil sides are to be placed, no grooves being made in the parts forming the actual poles. Peripheral grooves are also turned in the core in order that the ventilation of the copper and iron masses may be as complete as possible. Fig. 168 shows the completed field system of a turbo-alternator for small outputs. The gunmetal caps which can be seen at each

end of the core serve to keep the ends of the winding from flying out under the centrifugal forces, and it is noteworthy that the strength of these caps sets a limit to the peripheral speed attainable, for as a matter of fact it is sometimes necessary to use nickel steel (of low magnetic quality), instead of gunmetal, in order to procure the necessary strength.

When the machine is of a large size the core is built up of steel plates which are placed on a grooved steel hub and held in position by keys and end-plates. The grooves on the hub allow currents of air to pass through and to divide radially into the peripheral grooves, thus effectively cooling the winding and core.

FIG. 169



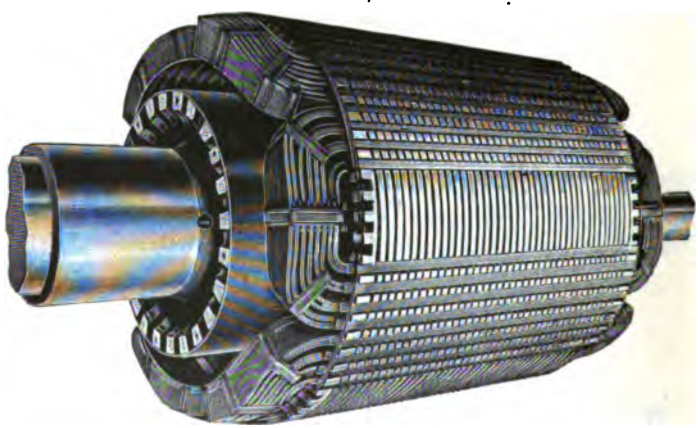
In figs. 169 and 170 such a field system is shown in two stages—(*a*) the hub and core without the winding; and (*b*) the hub and core with the winding in position and with the end caps removed.

In many cases the output demanded from a dynamo varies considerably at different times. For instance, four times as much power may be required to supply lamps at one time as at another. It is not economical to use one large machine, capable of meeting the maximum demand, and run it to give a small output at other times; but, fortunately, it is possible to join up two (or even more) alternating-current dynamos so as to feed the same circuit simultaneously when required, switching out and stopping one when the other is able to meet the low demand.

The armatures must not be joined up in series, but in parallel, and the machines may be driven by belts from the same shafting, or, if necessary, from independent engines running at about equal speeds. In practice the latter course is usually adopted, since it is uneconomical to employ a large engine to develop the power required by a small machine, which would be the case at periods of light load if two or more machines were driven from a common countershaft driven in its turn by a single large engine.

But parallel working is only practicable when in both machines the rates of alternation are equal, and the alternations 'co-phasal'—

FIG. 170



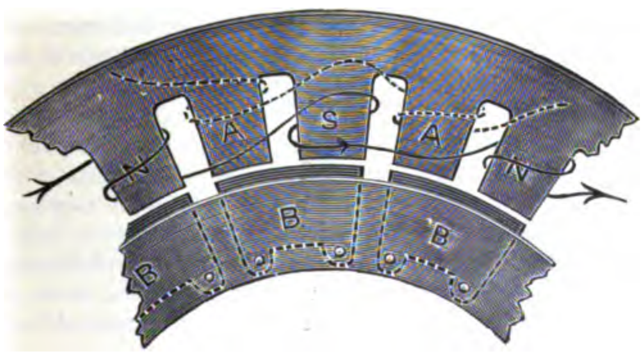
that is, when their maximum and likewise their minimum E.M.F.'s occur simultaneously. It is most remarkable that well-designed machines can correct each other and maintain this synchronism, but, as a most important part of the interaction depends upon the 'motor' properties of a dynamo, further consideration of the question must be deferred until electric motors have been dealt with.

The dynamo-electric machines which we have described in the preceding pages, although differing in detail, all have one feature in common—namely, that a coil or coils of wire wound on an iron core are made to rotate, and so give rise to the cutting

of lines of force by a moving conductor, or the cutting of a stationary conductor by lines of force, in order to produce the required electro-motive force.

There is another class of machine in which both the armature coils and the field-magnet coils are stationary, the cutting of the armature conductor by the lines of force set up by the field-magnet being effected by moving masses of iron in such a manner that first a very good and then a very bad magnetic circuit are alternately set up through the field-magnet and armature coils. There are several advantages possessed by this type of machine. The only moving part of the apparatus is a mass of iron which, if truly balanced, can be rotated at a high speed without involving

FIG. 171



any mechanical difficulties, such as arise when it is necessary to similarly rotate a complicated mass consisting of iron, copper wire, and various insulating materials ; and, further, since all the coils are stationary, reliable connection with the external circuit becomes an extremely easy matter.

Such machines are generally called 'inductor alternators,' and one of the earliest was designed by Mr. J. A. Kingdon, the principle of which will be gathered from fig. 171. The outer iron ring, which is stationary, has inwardly projecting pole-pieces which are wound alternately with armature and field-magnet coils. The armature cores are lettered A, and the dotted line indicates the manner in which the coils are wound round them ;

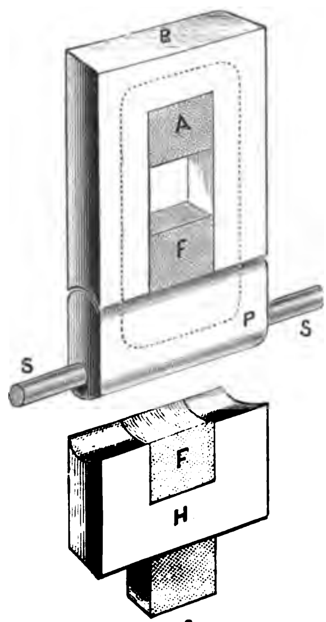
the field-magnet cores, which alternate in polarity, are lettered N S, and the winding of these coils is indicated by the full line with arrow-heads to indicate the direction of the exciting current. A steady current is maintained through the field-magnet coils, and the lines of force thus set up are changed in position and made to cut the armature coils by passing the masses of iron B in front of the pole-faces. These masses of iron, which are carried on a circular non-magnetic framework, are laminated to avoid eddy currents, and they are rotated at the necessary speed to produce the desired rate of alternation or periodicity. When they arrive in the position shown in the figure, the maximum number of lines passes from the adjacent field-magnet pole through each armature coil, and the E.M.F. is zero. As each mass or keeper B moves onward the air-gap increases and the number of lines of force threading an armature coil due to, say, a S pole is lessened; moreover, lines of force now begin to thread through the armature in the opposite direction from the N pole-piece which the keeper is approaching. The effective number is a minimum and the E.M.F. a maximum when the middle of each mass B is directly opposite the middle of an armature coil, because then two sets of lines of force equal in number but opposite in direction are passing through the armature coil, and when the magnetic circuit is again completed to the fullest extent the E.M.F. again falls to zero, each armature coil once more having the maximum number of lines of force projected through it, but in the opposite direction.

The principle thus involved is very interesting and may be applied in a variety of ways. In some instances the armature and field-magnet coils consist of two concentric coils of wire, as indicated in fig. 172, in which the field-magnet coil is the inner one, shown in section at F F, and the armature coil is the outer one, shown in section at A A. B is a U-shaped mass of iron which embraces both the armature and field coils on three sides; while H is a similar piece (equal in cross-section but having shorter limbs), which embraces the field coil only, the armature coil being placed outside its yoke. P is a mass of iron or a keeper carried by the shaft, S, which can be rotated rapidly, the shaft being at the centre of the two circular coils, F F and A A.

If a powerful steady current is sent through the field coil F F, a large number of lines of force will be developed and their arrangement will largely depend upon the iron pieces H and B, but more especially upon the position of the keeper P with respect to H and B.

When P is situated as shown in the figure it forms with B an almost complete magnetic circuit of low magnetic resistance round both coils A and F, and nearly the whole of the lines generated by the field coil in the vicinity of this iron circuit will also embrace the armature coil. In springing into this position (shown by the dotted line) the lines of force cut the armature coil transversely from the inner side, and give rise to a current, depending in E.M.F. upon the number of lines and the rapidity with which their position is changed. When the keeper is moved away there is a considerable air-gap offering a high magnetic resistance at the ends of the limbs of B, and consequently many of the lines of force collapse upon the coil F, cutting the armature from the outside as they pass into their new positions and generating an E.M.F. in the opposite direction to the previous one. Not only is the magnetic resistance of the path round the two coils made greater by the removal of P from the position indicated in the figure, but as P rotates it reaches a position where it acts as a keeper to the iron piece H, which embraces the field coil only, so that an almost complete magnetic circuit is then formed round the field coil, and nearly the whole of the lines of force pass through H and P and very few extend round A. Therefore, if the keeper P is rapidly

FIG. 172



rotated, the armature coil will be cut by a number of lines of force as they take up new positions, first outside and then inside it. It is evident, however, that with such a simple arrangement as that shown in fig. 172, not only would it be impracticable to obtain a high rate of alternation, but it would be impossible to make all the lines of force developed by the field core take either the one path or the other, many of those surrounding the coil at a distance from the fixed iron pieces being but little affected by the movement of the keeper; but it would evidently be an easy matter to increase the number of pieces of iron, and so dispose them that most of the lines of force would be influenced.

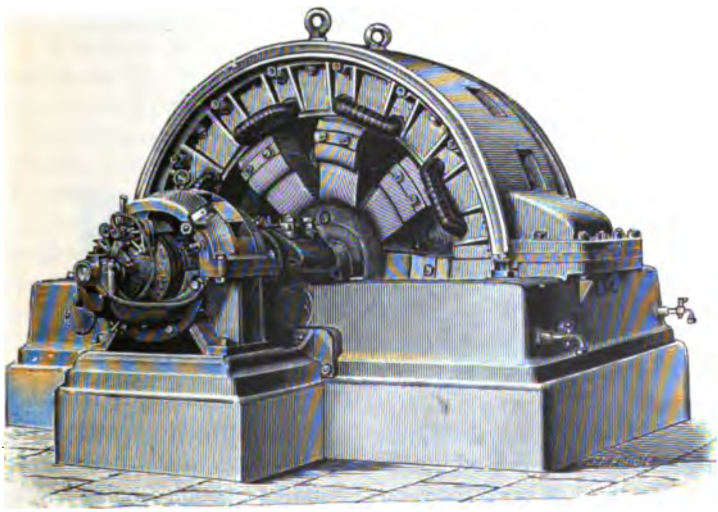
A number of machines have been designed and constructed upon the principles thus set forth or upon modifications thereof, but among them the alternator designed by Mr. V. A. Fynn deserves attention, for although of an early date, the most modern machines only differ from it in matters of detail. This machine presents several interesting points in design, and, what is often of great importance, runs practically noiselessly. The loud humming noise often set up by an alternating-current machine is chiefly caused by the vibration of certain parts (principally the laminated iron cores or pole-pieces), abrupt changes in the magnetic induction in certain parts of the magnetic circuit, and the churning of the air. In the Fynn alternator special attention has been paid to these three points, and the thin iron sheets forming the pole-pieces and the armature cores are so rigidly fixed that even their extreme ends cannot vibrate; the pole-pieces and edges of the slots in the armature core are so shaped that the lines of force 'tail off' gradually, thus avoiding sudden changes in the magnetic induction; while the moving part of the machine is of such a shape that it acts like a fan and maintains a comparatively steady draught of air through those parts of the machine which are liable to rise in temperature, instead of simply churning up the air.

The machine is of the inductor type, the armature being fixed and placed outside the field-magnet; the field-magnet is magnetised by a single coil which is also fixed, so that no brushes or sliding contacts are required to make connection either with the armature or field-magnet coil, the moving part consisting

solely of suitably disposed masses of mild steel and soft iron rotating inside the armature.

The particular machine to which we refer has an output of 125 kilowatts when driven at 375 revolutions per minute, the potential difference at the terminals being 2200 volts, and the rate of alternation 50 cycles per second. The field-magnet is excited by a small direct-current machine fixed upon an extension of the bed-plate and driven from the same shaft as the alternator. A general view of the alternator with its exciter is shown in fig. 173.

FIG. 173

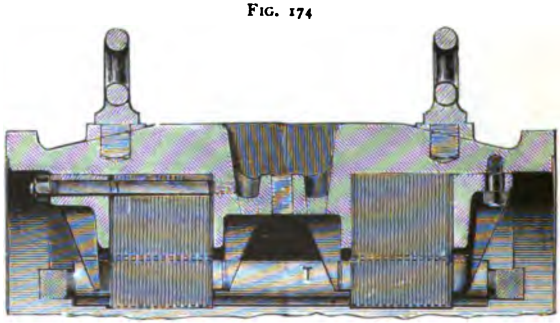


When the alternator is on open circuit the full potential difference at the terminals is obtained with a current of 20·5 amperes through the field-magnet coil, and this current needs to be increased only to 23·6 amperes to enable the machine to give its full-load current. As a matter of fact, at full load the power spent in the field-magnet coil is about 0·55 per cent. of the full output of the machine. A series of tests made upon this machine showed that it possesses good regulating properties, as when driven at a constant speed with a constant exciting

current, the drop in potential at the terminals between no load and full load was 100 volts, or 4·5 per cent. of the maximum pressure. When the machine was overloaded up to a total of 175 kilowatts the drop was 190 volts, or 8·6 per cent. of the maximum voltage.

The outer framework of the armature is of cast iron, in two pieces, and it holds rigidly in position the laminated armature core, which consists of a large number of thin soft-iron sheets insulated with paper and projecting inwards. These laminated core-plates project inwards about one inch clear of the edges of the cast-iron framework; but, as they are clamped between quarter-inch wrought-iron plates, even their free ends are held

FIG. 174



rigidly in position and vibration is prevented. At sixteen points round the inner circumference the core-plates are slotted out to receive the armature coils, corresponding openings being left in the cast-iron framework. A section through the upper part of the armature is shown in fig. 174, from which it will be observed that the core-plates are not continuous in a direction parallel to the armature shaft, but that they are divided into two distinct sections, separated by a considerable air space inwards, but magnetically yoked together on the outer circumference by the cast-iron framework. The reason for this will be apparent presently, when the relative positions of the field-magnet pole-pieces have been described. The armature winding offers a resistance of slightly over a quarter of an ohm, and it consists of sixty-one No. 20

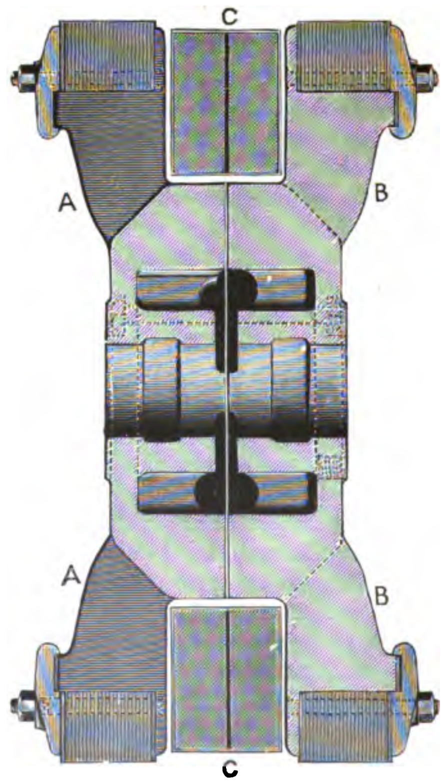
standard wire-gauge copper wires stranded together and effectively insulated with two layers of cotton braided over and treated with shellac varnish. There are eight coils, rectangular in shape, symmetrically placed round the inner circumference of the armature, the whole of the coils being joined in series. Each of the two longer or active limbs of the armature coil (that is to say, the two limbs parallel to the driving shaft) is wound in a special insulating tube T, and the tube with the coil is held in position by a hardwood strip driven inside the edges of the opening. The shorter limbs of the rectangular coils which stand out clear of the framework and the paper tube are heavily insulated with prepared tape, rubber, and shellac varnish.

A section of the field-magnet with the stationary coil C is shown in fig. 175. There are eight pole-pieces on each side of the coil, and the lines of force thus set up by the exciting current make all the pole-pieces on one side of the coil (say at B) of south polarity, and all on the other side (say at A) of north polarity. The two sets of pole-pieces are not, however, placed symmetrically opposite each other, but are 'staggered'—that is to say, the left-hand set of pole-pieces is fixed $22\frac{1}{2}°$ ahead of the right-hand set, so that every north pole on the one side comes exactly midway between two south poles on the other side. This is indicated by the section shown in fig. 175.

The manner in which the direction of the lines of force is reversed simultaneously through all of the armature coils will be gathered from the diagram, fig. 176. The pole-pieces of south polarity are shown immediately under the armature coils, and when these pole-pieces are exactly opposite the middle of the coils the pole-pieces on the other side of the field-magnet—viz. those of north polarity—come midway between adjacent coils, the spaces between the coils being exactly equal to their width (see fig. 173). In this position, lines of force pass upward from the north poles of the field-magnet into those parts of the armature core not encircled by wire, across the cast-iron framework, and then down through the armature coils into the south poles of the field-magnet. When the field-magnet has rotated through an angle of $22\frac{1}{2}°$ from this position, all the north poles are directly under the coils (at the opposite end), while the south poles are then under the spaces

between adjacent coils, so that the lines of force due to the field-magnet now pass through the armature coils in the reverse direction, and this reversal takes place periodically as the field-magnet is continuously rotated. It should be noted that, although the lines

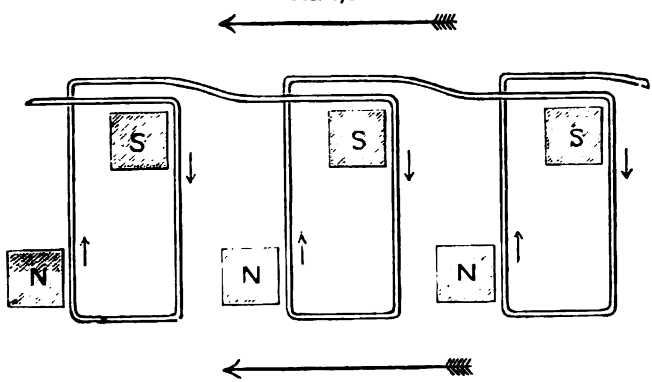
FIG. 175



of force are reversed through the armature coils, they are not reversed through the armature core or any part of the iron. This happens because the poles passing any given part of the armature core are always of the same polarity, and the lines of force through the iron thus simply rise to a maximum and fall to a minimum.

The air-gap between the pole-pieces and the armature core is very small, and this, added to the fact that the induction through the field-magnet poles is not high, tends to prevent the lines of force spreading from the poles and leaking into parts of the machine where they could not act effectively. A small air-gap, however, also allows the lines of force set up by the current in the armature to pass readily through the field-magnets, and as these lines are generally in a direction opposite to those of the field proper, they tend to weaken the field and so reduce the E.M.F. developed. This reaction of the armature on the field-magnet is greatest when the armature current is greatest, and hence causes

FIG. 176



the E.M.F. to fall off when the load increases; or, in other words, a machine of this description with a small air-gap generally regulates badly. In the Fynn machine the resistance of the magnetic circuit through the field-magnet is increased and the reaction of the armature diminished, not by increasing the air-gap at the pole-faces, but by introducing a gap of about an eighth of an inch across the core which yokes the two sets of magnet-poles together, as already explained. This of course entails an addition to the ampere turns required to magnetise the field-magnet, but it enables the advantages attending the small air-gap between the magnet and the armature to be retained without reducing the self-regulating capabilities of the machine.

CHAPTER IX

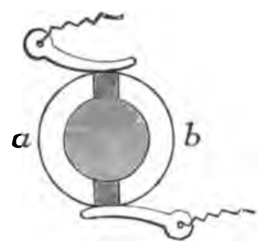
DYNAMO-ELECTRIC MACHINES (DIRECT CURRENT)

ALTHOUGH the sphere of usefulness for alternating-current dynamos has largely increased of late years, there is still a vast amount of work which such machines are wholly incompetent to perform. This is notably the case in connection with the deposition of metals by electricity, and in the 'charging' of secondary batteries. For these, and several other important purposes, it is essential that the currents should be continuous, and flow in one direction only. Except in the case of a few experimental machines, the current which is generated in the armature always alternates in direction; but it is possible to arrange matters so that all the currents so generated shall be made to flow in one direction *in the external circuit*, the process being known as 'commutation,' and the part of the machine by which the alteration is effected is termed the 'commutator.' Directly this has been successfully performed, the dynamo is capable of a new and important development, for it is then possible to use all or a part of the current which is generated in the armature, for the purpose of magnetising the field-magnets. The smaller auxiliary machine, which, in most of the dynamos previously described, is employed to excite the field-magnets, can consequently be dispensed with, and the machine made 'self-exciting.'

We come then to the consideration of the means to be employed in order that the currents which are generated in alternate directions in the armature itself can be commutated so as to flow in one direction *in the external circuit*. Referring again to fig. 138, we remember that the *direction* of the current is unaltered (although it varies in E.M.F., and therefore also in strength) during

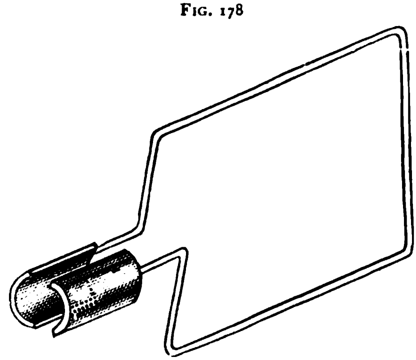
the first half-revolution of the rectangle, and that, at the end of that half-revolution, the reversal in direction takes place. Now, a moment's reflection will show that if, just at the end of this first half-revolution, the positions of the two brushes on their respective rings were instantaneously interchanged, the current generated during the second half of the revolution would flow in the same direction round the external circuit as the preceding current did, because, although really generated in the reverse direction, it is entering the external circuit at the other end. This is the fundamental principle of commutation; only, instead of shifting the brushes, the change is effected at the right moment by a modification of the ring or rings against which the brushes press.

FIG. 177



The simplest possible form of commutator is shown in section in fig. 177. Instead of two brass rings, a single brass ring or tube is employed, but with the difference that it is split lengthways into two halves or segments, *a b*, insulated one from the other. Each end of the rotating coil of wire is connected to one of these segments, and the brushes or flat springs (which are permanently connected one to each end of the external circuit) are so situated that they press upon the insulating divisions between the segments at the moment that the coil is in the vertical position—that is to say, in the position where the reversal of the current takes place. Just at that moment, then, the ends of the coil in contact with the respective brushes are also reversed, and the result is that when the coil is rotated uniformly, a succession of short currents passes through the external circuit,

FIG. 178



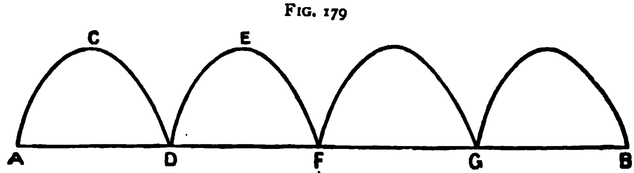
each current rising and falling similarly, but all impelled through the external circuit in the same direction.

This will be rendered more clear by a reference to fig. 178, where a coil consisting of a single rectangular convolution is shown with its ends connected to the commutator sections or 'segments.' It is evident that the length of the wire can easily be increased by winding it in a number of convolutions, instead of in a single rectangle, when, as a matter of course, the E.M.F. will be increased proportionately.

The variation in the E.M.F. developed by an ideal alternating-current dynamo is shown in fig. 143, where the line A B represents the normal or zero potential, the curves above it indicating the gradual rise and fall of, say, the positive potential, and those below it the opposite, or negative potential.

Fig. 179 exhibits, in a simple manner, the result of replacing the two metal rings by a split tube, or simple two-part commutator (assuming the distance between the two parts to be very small).

FIG. 179

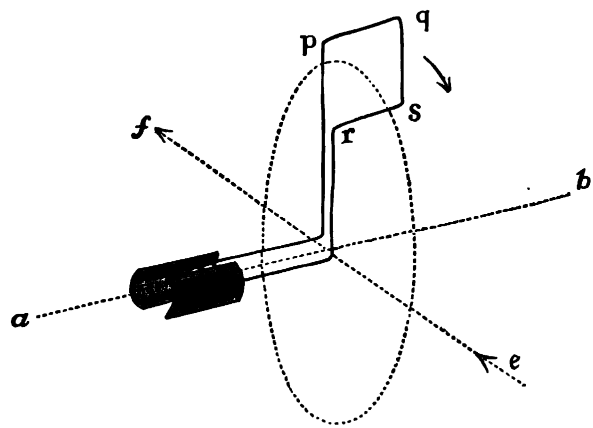


A B again indicates the zero potential, and the curve A C D the varying potential developed during the first half-revolution; but, instead of the second half-revolution developing in the external circuit a negative potential, it is commutated into an external positive one, D E F, so that a series of currents, each of brief duration, is urged through the external circuit in one common direction. The total amount of electrical energy developed is, however, the same as before, although the potential and therefore also the current strength oscillate between zero and the maximum.

A current varying so much in strength is of almost as little service for many purposes as an alternating current; for, in most cases, the current is required to be not only uniform in direction, but also constant in strength.

The methods by which an almost steady current can be obtained will be understood more easily when studied in connection with an armature constructed of coils wound on a somewhat different system. In fig. 180, *a b* indicates the axis of rotation, and *p q r s* a single loop of wire which travels round the circular path indicated by the dotted circle, it being assumed that a uniform field is maintained throughout the whole of the space traversed by the wire. If we suppose the lines of force of the field to be in the direction of *e f*, along, or parallel to, a diameter of this circular path, then they will be cut by the coil in a manner somewhat

FIG. 180

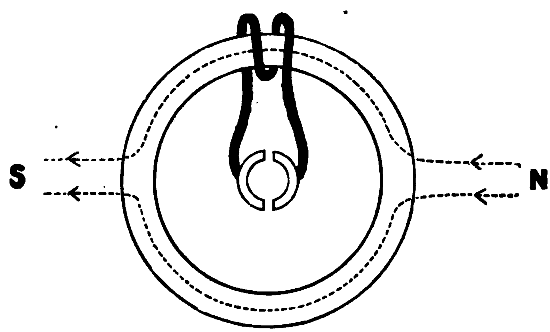


similar to that of the rectangular coil which we have previously considered. The movement from the vertical position through the first half-revolution produces a current which rises to a maximum when the coil has turned through an angle of 90°, and falls to zero again when the coil reaches 180°, while the current generated in the next half-revolution is exactly equal in strength, at corresponding positions, though opposite in direction; but it can be commutated in precisely the same way as in the case of the ordinary rectangular coil, illustrated in fig. 178.

There is, however, one great difference between the two methods. No portion of the coil shown in fig. 178 acts prejudi-

cially, although the portions connecting the horizontal limbs are always idle, inasmuch as they do not cut, but only slide through, the lines of force. With the coil shown in fig. 180 the case is different. There are still two idle connecting lengths, *p r* and *q s*, but the E.M.F. induced in the two horizontal limbs *p q* and *r s* is in the same direction in each—say from *p* to *q* and from *r* to *s* —because they always cut the lines in a similar sense, although at different rates; they therefore act in opposition to each other, each developing an E.M.F. which strives to set up a current in the opposite direction to the other round the coil. But the outer limb *p q* traverses a greater portion of the field than does *r s*, and consequently it cuts lines of force at a greater speed than does *r s*,

FIG. 181



whence the E.M.F. generated by it is the greater, and the resulting current round the coil is therefore that due to the preponderance of the E.M.F. of the limb *p q* over that of *r s*. Now, the lines of force which the outer limb cuts in excess of those cut by the inner limb when the coil has moved through an angle of 90° are simply those which pass through the coil when it is in the zero position, as in fig. 180, and it is evident that if the field is uniform, and the coil comparatively small, the lines thus embraced will be very few indeed, and the use of iron to increase their number immediately suggests itself. It is most advantageous to make the iron in the form of a ring, as shown in fig. 181, and cause it to rotate with the coil. The coil here depicted consists

of two convolutions, and the dotted lines indicate the general direction of the lines of force through the iron when it is placed in the field between two opposite magnet-poles. It must be clearly understood that in such a case the lines of force will not rotate with the ring, but remain practically fixed in position, finding new points of entry and exit on the surface of the iron as the ring rotates.

The effect of so placing a ring of iron in a magnetic field is illustrated more precisely in fig. 182. The apparatus employed

FIG. 182

to obtain this figure consisted of a quantity of thin soft-iron wire wound into a ring, and placed between the opposite poles of two powerful bar-magnets, a sheet of paper being laid over the ring and magnets, and iron filings sprinkled upon it. The spaces free from filings represent those places where the permeability of the iron is sufficiently high to prevent any appreciable number of lines of force extending above the paper so as to give direction to the filings. The manner in which the lines converge into the

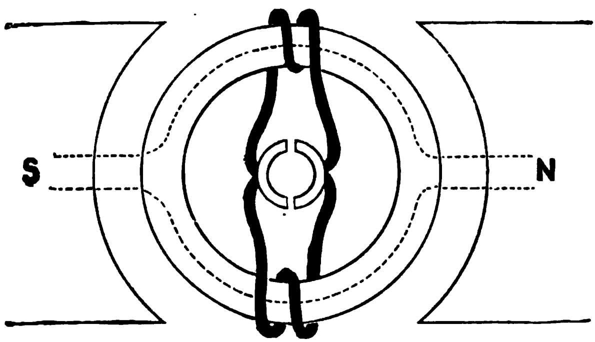
ring should be noted, and it will also be observed that at two places, on a diameter at right angles with the lines, the magnetic effect above the paper is considerable. The reason for this is that the greatest number of lines pass through the iron at these points, and the density of the lines here is so great that the permeability is sufficiently reduced to allow some lines to leak above the paper. Comparatively few lines pass diametrically across the interior of the ring, about half of them going through the upper and half through the lower part of it. Consequently the inner limb of the coil (fig. 181), if wound over and rotated with such a ring, would cut but very few lines, and the resulting E.M.F. would be practically that developed by the outer limb alone.

In the case illustrated in fig. 181 only one-half of the total number of lines of force urged through the iron can, at any one time, pass through the coil, and some device is therefore necessary to enable the other half to be utilised. Now, since the induced E.M.F. will be the same in any given position after the coil has passed the point situated 180° from zero as it was in the corresponding position after it had passed the zero point itself, it is clear that a second coil might with advantage be placed at the opposite extremity of a diameter of the circular path described by the coil, as the joint effect of the two coils could then be made use of. We will assume that the limbs on the outer periphery alone are active, and it will be seen that if the induced current flows from front to back in the outer limbs of the upper coil, it will flow from back to front in the outer limbs of the lower coil, because these limbs always cut the lines from opposite sides, viz. the former from above and the latter from below. The E.M.F. is, however, at any moment equal in each, and, by joining the two ends which are at a positive potential to one segment and the two ends which are at a negative potential to the other segment, both coils are made to deliver their currents in the same direction to the external circuit.

Fig. 183 illustrates the arrangement for employing two such coils; they are similarly wound (right-handedly in this case), and their *adjacent* ends are joined to the same section of the commutator. Now, as they are fixed at opposite extremities of a diameter, they pass at every moment through parts of the field where they act with equal effect, and therefore, as already pointed out, the

E.M.F. will be the same at the extremities of each coil. Since the ends of the two coils, which are at the same E.M.F., are joined to the same segment of the commutator, the E.M.F. due to both coils is only the same as that produced by one of them, and the current will rise and fall in precisely the same manner as with a single coil. It is, in fact, an exactly analogous case to that of joining two primary cells of equal E.M.F. in parallel. There is also the corresponding advantage here that because the coils are joined in parallel the internal resistance between the two segments is only half that of one coil, and any arrangement that so reduces the internal resistance of a current-generator may be sometimes very valuable. By increasing the number of turns in the

FIG. 183

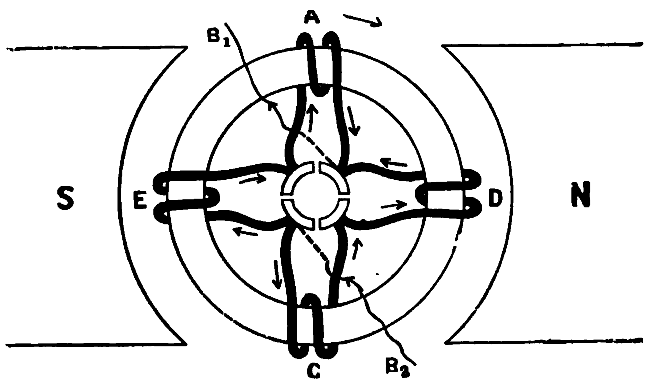


coils we can increase the E.M.F., because a greater number of conductors in series, round the periphery, are then usefully cutting lines of force; but, of course, the number must be exactly the same in each coil, otherwise the E.M.F. set up in the two coils would be different. In figs. 181 and 183 it will be observed that there are two active conductors to each coil.

We are now in a position to proceed with the consideration of a method for making the short fluctuating currents depicted in fig. 179 approach more nearly to a continuous steady current. These short currents are at a minimum when the coils are at right angles to the lines of force, or at that point where the reversal of the induced current takes place, and it is evident that if a second

pair of coils be placed at right angles to this existing pair, as in fig. 184, they will always lie parallel to the lines of force, or be in the position of best action, just at the moment when the first pair are almost idle. But it now becomes necessary to divide the commutator into four parts, all the coils being, of course, similarly wound, and the adjacent ends of adjacent pairs connected to the same segment of the commutator. When only two segments are employed, the brushes, as we have observed, are placed so that the divisions of the commutator pass them just at the moment when the coils are at right angles to the lines of force, and when they are almost idle. In the present case, with four coils, the

FIG. 184

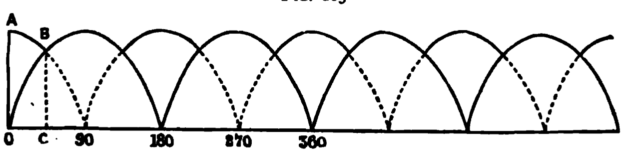


brushes must also be placed so that the division between each pair of segments on the commutator passes a brush when the coil connected to that pair of segments is in the position of least activity, viz. with its plane at right angles to the lines of force. We shall see presently that there are several causes which combine to slightly vary this particular position, although it can always be found.

In fig. 184 the brushes are indicated by dotted lines, and are shown slightly out of what we have hitherto considered to be their correct position. Supposing the lines of force to pass straight across from one pole-piece to the other, the currents in the various coils would flow in the direction indicated by the arrows and the

resulting current could be led from the armature to the external circuit by the upper brush B_1, entering the armature again by the lower brush B_2. The two horizontal coils D and E are in the position of greatest activity, while the vertical coils A and C are almost idle, and merely serve to conduct the current generated by the active coils to that segment of the commutator which the brush is touching. A moment later A and C will each begin to generate a current in the opposite direction to the one now flowing in them, but as by that time they will have passed the brushes, their opposite ends will now be in contact with these same brushes, and the direction of the current in the external circuit will remain unaltered. When the plane of each of the four coils makes an angle of 45° with the lines of force, they are all equally active (although the activity of no one coil is then so great as that of the coils E and D while they are in the best position, as shown in fig. 184), and the

FIG. 185

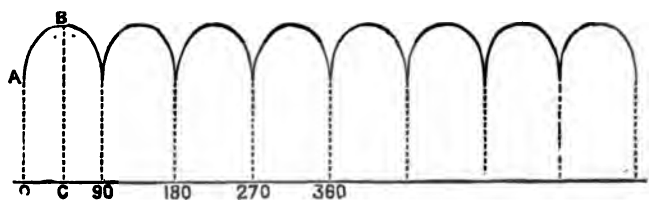


E.M.F. at the brushes is twice that which is at that moment being developed by one coil.

The resulting E.M.F., due to the joint effect of the double instead of the single pair of coils, is still far from constant, and, as before, we must determine at what positions of the coil this resulting E.M.F. is at a maximum and where it becomes a minimum. The curve already given (fig. 179) illustrates the variation of the E.M.F. due to one coil or one pair of coils, and as when this E.M.F. is highest, that of the second pair of coils is lowest, and *vice versâ*, the relative magnitude of the E.M.F. generated by two pairs of coils at different positions may be indicated by the overlapping curves in fig. 185. From this we have to construct a curve which shall show how the E.M.F. *at the brushes* due to the joint effect of both pairs of coils varies. Now, as twice during each revolution one of the two pairs is for the moment acting alone, the E.M.F. at the brushes is then simply that due to this pair, and is proportional

to the length of the perpendicular line O A. At this moment the E.M.F. at the brushes is at its lowest value, and the length of this line O A determines the lowest point on the curve which we desire to construct. Immediately after this point is passed both pairs are acting together, the activity of the one increasing and that of the other decreasing. At a certain stage they will be acting with exactly equal effect, and this stage is indicated by the intersection of the two curves in B; it occurs, as we have seen, at the moment when each coil makes an angle of 45° with the lines of force. To obtain, therefore, the resulting E.M.F. at the brushes, we must add together these two equal E.M.F.'s; consequently, twice the length of the line C B must be taken as the height of this the highest point in the new curve. When the coils have rotated through another 45°, one pair is again idle and the other

FIG. 186



at its maximum activity, so that we again reach the lowest point of the curve. The curve so constructed is shown in fig. 186, and it indicates the manner in which the total E.M.F. at the commutator brushes fluctuates when the armature consists of two pairs of coils arranged as in fig. 184. The resulting current will also fluctuate similarly, depending in strength upon the total resistance in the circuit.

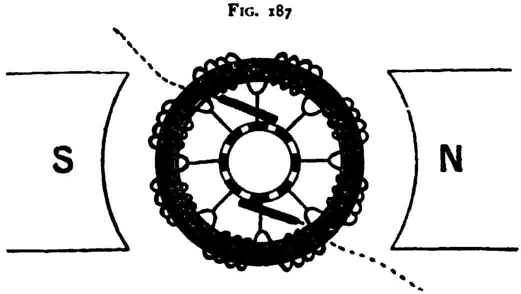
It is obvious that the variation in the E.M.F. can be further diminished by the employment of a yet greater number of pairs of coils in the armature, provided that they are all placed symmetrically.

For instance, a coil might be placed exactly midway between each of those wound on the armature shown in fig. 184; the armature would then consist of eight coils in four pairs, and the commutator of eight bars or segments (fig. 187). The black

portions of the circle represent the metallic segments, the white spaces between them indicating the insulating material. The current from such an armature would be far more steady than one from the four-coil armature; in fact, it may be stated generally that the greater the number of coils composing the armature, the less the fluctuation of the current. Of course there is a practical limit to the number of coils; for instance, the commutator with this kind of armature must have as many segments as the armature has single coils or sections, and its construction and the making of the necessary connections would be difficult and expensive if the number were excessively increased.

It will be observed that in fig. 187 the whole armature conductor is wound continuously round the core; it is divided into

FIG. 187



sections having four convolutions each, and a connecting wire is led from the junction of every two adjacent sections to the proper segment of the commutator. The result is of course the same as if the ends of each section were brought direct to the commutator segment, while the actual length of the armature conductor, and therefore the resistance, is slightly reduced. In this and the following chapters, illustrations will be given of the way in which these commutator connections are effected in practice.

In order to increase the E.M.F. developed in a given field at a given speed, we must increase the number of conductors on the outer periphery of the armature, which can be done by adding to the number of convolutions, although this also increases the internal resistance. In the armature illustrated there are thirty-two active portions of the wire round the whole external periphery,

but as they are joined up in two sets in parallel, the total E.M.F is only sixteen times that of one active portion.

If we know the number of active conductors joined in series and the number of lines of force which they cut per second, it is easy to calculate the resulting E.M.F. The E.M.F. developed at any moment by any particular conductor moving circularly in a uniform field varies with its position, and at any moment it is, as we have seen (Chapter VIII.), proportional to the cosine of the angle which the plane of the coil of which it forms a part makes with the lines of force; or to the sine of the angle through which the coil has turned from its position at right angles to the lines of force. But we need not now trouble ourselves with this consideration; for, in a symmetrically constructed armature of many convolutions, the place of each conductor as it moves to a position of greater or less activity is immediately filled by another, and the total E.M.F. remains unaltered. Since each active length undergoes precisely the same inductive effects, the average E.M.F. induced in each is the same, and the total E.M.F. will be equal to the number of active conductors round one half of the armature multiplied by the average E.M.F. developed by one of them during half a revolution. This average E.M.F. is of course the same as that developed during a whole revolution.

Supposing the armature to consist of forty-eight convolutions, and the average E.M.F. developed by one of the active limbs to be 2 volts, then the whole E.M.F. would be $2 \times 24 = 48$ volts.

The average E.M.F. developed by each active conductor depends upon the speed at which it moves, and the number of lines cut by it; in fact, we have seen that if a wire, one centimetre long, is moved at a velocity of one centimetre per second transversely through a field of unit strength (that is, a field having one line of force per square centimetre), then the resulting E.M.F. will be equal to one C.G.S. unit. This unit being so very small, the volt is employed for practical use, having a value 10^8 or 100,000,000 times that of the C.G.S. unit; so that after calculating E.M.F. in C.G.S. units, the result must be divided by 10^8 to obtain the E.M.F. in volts.

It is preferable to consider the number of lines cut per second, which number can always be found, and then we need not know

the length of the conductor or the intensity of the field in C.G.S. units, nor need any difficulty arise even if the field be not uniform. Referring again to fig. 187, suppose there are 16,000 lines of force urged through the armature core, these lines will all be cut twice by each conductor during one complete revolution. If the armature makes one revolution per second, each conductor will cut 32,000 lines per second and generate an average electro-motive force of 32,000 C.G.S. units. And as there are sixteen conductors in series, the total average E.M.F. as measured at the brushes will be $16 \times 32{,}000 = 512{,}000$ C.G.S. units, or

$$\frac{512{,}000}{10^8} = \cdot 005 \text{ volt nearly.}$$

If the armature made ten revolutions per second, the E.M.F. would be ten times greater (i.e. 0·05 volt) because each conductor would now cut ten times the number of lines per second.

In fact, we may say that the average E.M.F. generated in an armature of this description is equal to

$$N \times \frac{P}{2} \times 2n, \text{ that is, } N P n \text{ C.G.S. units,}$$

or

$$\text{average } E = \frac{N P n}{10^8} \text{ volts,}$$

where N is the total number of lines of force urged through the armature core; P the total number of active conductors lying round the periphery, and $\frac{P}{2}$, therefore, the number in series; n the number of revolutions per second, and $2n$, therefore, the number of times per second which the whole of the lines are cut by each conductor.

The E.M.F. obtained in the last example (0·05 volt) is very low, because both the number of active conductors and the number of lines of force assumed are small. In practice it is not unusual to force several millions of lines through the armature core. Supposing the number to be 3,000,000, and the number of conductors round the periphery to be 150, then if the armature is driven at

1200 revolutions per minute, or 20 per second, the E.M.F. developed would be

$$\frac{3{,}000{,}000 \times 150 \times 20}{100{,}000{,}000} = 90 \text{ volts.}$$

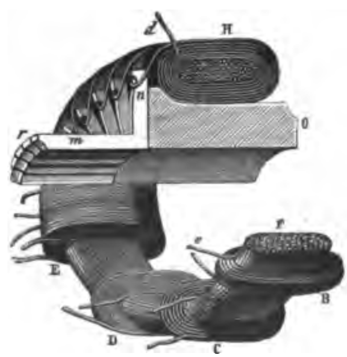
The above is a fair example of what obtains in actual practice, and the student will readily perceive that it is necessary for the quantity of iron in the armature core to be considerable, otherwise with such a large number of lines of force the magnetic induction through it (that is, the number of lines per square centimetre) would be abnormally high. We know that the permeability of iron decreases rapidly when the induction through it exceeds a certain amount, and then a large number of the lines leak diametrically across the ring instead of taking the path indicated in fig. 183, many of them passing across the steel driving-shaft, the permeability of which may then be equal or even superior to that of the 'saturated' iron.

Now, as these lines of force thus leaking across the ring are cut by the inner portions of the conductor (equivalent to *r s* in fig. 180) and act prejudicially, inasmuch as the E.M.F. generated by the inner wires in cutting them is reverse to the main E.M.F., it is evidently inadvisable for this reason, if for no other, to endeavour to push the induction too far. As a rule the limit is from 16,000 to 18,000 lines per square centimetre, and if more lines through the core are needed, either the area must be increased or iron of higher permeability employed. The former necessarily entails a greater length of conductor. It is evident that in an armature of the type we are considering, the iron of which the core is made should be of the highest possible permeability, while the quantity of iron or steel used inside the ring should be as small as possible to minimise the tendency to cross-leakage. This latter consideration implies that iron should not be employed for the purpose of mechanically connecting the ring to the driving shaft. In practice, gunmetal or some other non-magnetic alloy is used.

The first armature on this principle was constructed by Pacinotti, but it remained unnoticed until the essential features had been combined in a slightly different form by Gramme.

Fig. 188 illustrates the construction of an early form of Gramme armature, the core being shown cut through, and some of the coils displaced to make it clearer. The core, F, consists of a quantity of iron wire wound continuously to form a ring of the shape shown by the section. Over this were wound about thirty coils of insulated copper wire, B C D, &c., the direction of the winding of each being the same, and their adjacent ends connected together. The commutator segments consist of a corresponding number of brass angle-pieces, *m n*, which are fixed against the wooden boss, O, carried on the driving shaft. The junction of every two adjacent coils is connected to one of the commutator segments, as shown at *n*, and in the completed machine two flat brushes of copper wire would be pressed against the projecting ends of the segments, and serve to deliver the current to the external circuit.

FIG. 188



The latest forms of this armature, although identical in principle, are far superior from a mechanical point of view; in fact, the armature here illustrated would fly to pieces if subjected to the stresses which occur in a modern machine. It is necessary that the commutator bars should be firmly held in position, that the wire of the coils should be bound or, by some means, fixed so as to prevent its being shifted, and that the core and with it the coils should be firmly secured to the driving shaft. It will be shown, in describing the best types of machines, how these points are attended to in practice.

Especial care must be taken to prevent the generation of eddy currents in the core, and this was Gramme's reason for using rather fine wire instead of a solid ring of iron. We have previously remarked that the E.M.F. which gives rise to these eddy currents is very low (although the current strength may be considerable, because the large mass of metal involved offers little resistance),

and that, therefore, the merest film of insulation between neighbouring wires of the core is sufficient. Except in special cases a coating of shellac varnish is all that is required, but in any case the space occupied by insulation should always be as small as possible, so as to allow the maximum amount of iron to be used in a given space. If the armature is rotated in a simple field between two pole-pieces, it is not necessary to subdivide the core to the extent adopted in the earlier Gramme machines, for since the direction of the eddy currents is at right angles to the lines of force and to the direction in which the core moves, there will be no tendency for them to flow in a radial direction, but only along lines parallel to the driving shaft. Therefore the core may be simply laminated, or built up of a number of thin discs or thin

FIG. 189

flat rings of soft iron, thus giving better facilities for mechanical connection with the shaft, and also reducing the magnetic resistance considerably. In entering or leaving the interior of the wire core, the lines of force have to leap across numerous little spaces of low permeability, while in the case of a core built up of discs, not only is the mass of iron greater, but it is also continuous in the direction of the lines, and discontinuous only in the path which would be taken by the eddy currents.

A complete armature of the so-called Gramme ring type is shown in fig. 189. The core consists of a number of very thin flat rings of well-annealed charcoal iron, the outer diameter of each ring or disc being 11½ inches, and its inner diameter 9¼ inches. Sheets of thin paper insulate each disc from its neigh-

bours to prevent the flow of eddy currents. The armature is mounted on a Bessemer-steel shaft to which is keyed a four-armed gunmetal spider, and the extremities of the arms of this spider fit into notches cut in the inner edges of the soft-iron core rings, so that a good mechanical connection is obtained between the core and the steel shaft. The spider is made of a non-magnetic metal, to reduce the tendency to leakage of lines of force across the interior of the armature, as already explained.

The armature conductor consists of cotton-covered copper wire of No. 9 standard wire gauge, lying round the core in one layer, and offering a resistance, from brush to brush, of 0·048 ohm. There are two convolutions in each section, the adjacent ends of neighbouring sections being soldered to radial lugs projecting from the commutator bars, as shown in fig. 189. There are seventy-six such sections, and, consequently, seventy-six bars in the commutator, these bars being of hard-drawn copper insulated from each other by mica strips 0·75 mm. in thickness. Mica is almost the only material now used for this purpose, for which it is eminently suitable, because of its excellent insulating properties, its great durability, and its practically perfect cleavage, in consequence of which it can be procured of any desired thinness.

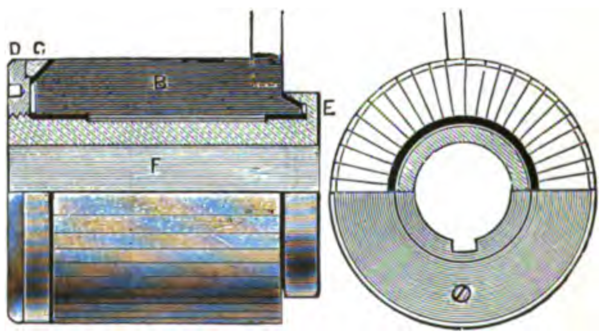
As the length of conductor parallel to the shaft is considerable, there is a risk of its bulging out when rotated at a high speed, a tendency which would be assisted by the drag on the conductors due to the field, and by the rise in temperature and consequent expansion of the wire caused by the current itself. Any such bulging out or stripping of the conductor is prevented by binding the armature with several turns of fine strong wire in three places, as shown in fig. 189.

The commutator always forms an important part of a dynamo. In almost every instance the segments are made of hard-drawn copper and insulated from each other by means of mica, but there are many different methods of rigidly securing the segments in position and insulating them from the shaft. One method is illustrated by the two views given in fig. 190, the upper half being shown in section in each case. Upon the steel shaft F is keyed a gunmetal bush, E, with a rim at one end recessed to receive the projections from the commutator bars or segments, B.

The opposite corner of these bars is shaped to fit a steel ring, C, of triangular section, which is held tight home by the wrought-iron nut, D, screwed on to the gunmetal bush. The bars are insulated from the bush E and ring C by sheets of vulcanised fibre, indicated by the thick lines in the figure.

Returning now to a consideration of the phenomena developed by the actual rotation of the armature, we may repeat that the brushes must be so placed that every division between the segments of the commutator passes under a brush just at that moment when the coil, the ends of which are connected to those segments, is idle. Now this happens when the plane of the coil is at right angles to the lines of force, so that if the lines of force always

FIG. 190



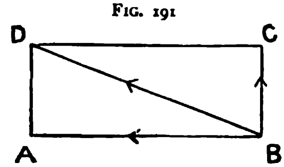
retained their regular straight direction between the poles of the field-magnet, or even if they curved regularly through the iron core as indicated in fig. 183, it would be easy to fix the correct position for the brushes. But the field is distorted immediately the armature is caused to rotate and the current established. This distortion is due to the fact that the armature itself becomes a powerful electro-magnet, having lines of force which are not coincident with those of the field-magnets. The two halves of the core are, as a matter of fact, magnetised by the currents passing round them, and in such a manner that their similar poles are adjacent to each other and situated at the points where the two currents enter and leave the external circuit. Now, if two

semicircular magnets of equal strength are placed so as to form a circle with their *unlike* poles adjacent, they form a complete closed magnetic circuit, nearly all the lines of force taking the path of the iron or steel, and there is consequently very little external magnetic effect observable. But if these same semicircular magnets are placed with their *like* poles adjacent, there is abundant external evidence of the magnetic strength of the combination. The circle acts, indeed, as if it were a single magnet, the distance between its poles being the length of the diameter. Some of the lines of force find their way back across the diameter to the opposite pole, while others pass round outside the circle, a much larger proportion taking this course, when, as in the case of a dynamo, there are large masses of iron in the vicinity.

The position of the brushes determines the position of the poles of the armature, since they form the meeting-points for the currents in the two halves of the armature, and when the brushes are placed on a diameter at right angles to the lines of force of the field, these poles are also at right angles to those lines of force.

It is manifest that as the tendency is for the armature to generate a magnetic field in one direction, while the field-magnets strive to maintain one in another, the direction of the resultant field must lie between the two, the exact position depending to a great extent upon the relative magnetising forces of the armature and field-magnets. Were these relative forces known, the direction of the resulting field might be determined approximately by the well-known 'parallelogram of forces' (see fig. 191). In this case the line A B represents by its position the direction, and by its length the magnitude, of the magnetising force due to the field-magnets alone, while the line B C, drawn at right angles to A B, represents the direction and force of the field due to the armature. Then the diagonal B D of the completed parallelogram represents both in magnitude and direction the resulting magnetic field, when the brushes are placed on a diameter at right angles to the direction of the field represented by A B. If, however, we wish to place the brushes on a diameter

FIG. 191

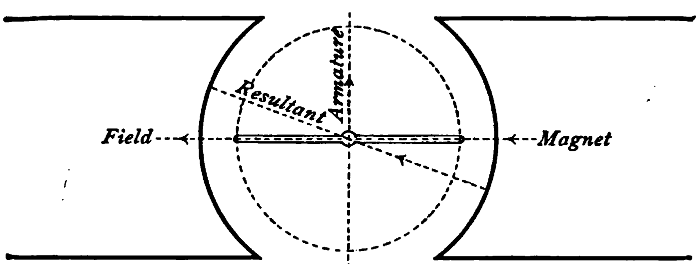


at right angles to the resulting field B D, it is necessary to shift them so that B C is perpendicular to B D.

The relation between the fields due to the field-magnet and to the armature and the consequent or resultant field is illustrated in a slightly different manner in fig. 192, which needs no further explanation.

The altered position of the brushes is commonly known as the *lead* given to them, and the angle through which they are moved is known as the angle of lead. In every dynamo the lead is forward or in the direction of the rotation of the armature. The parallelogram of forces referred to above does not exactly indicate the true angle, however, as the method would only be applicable if the field-magnets completely embraced the armature. It will

FIG. 192

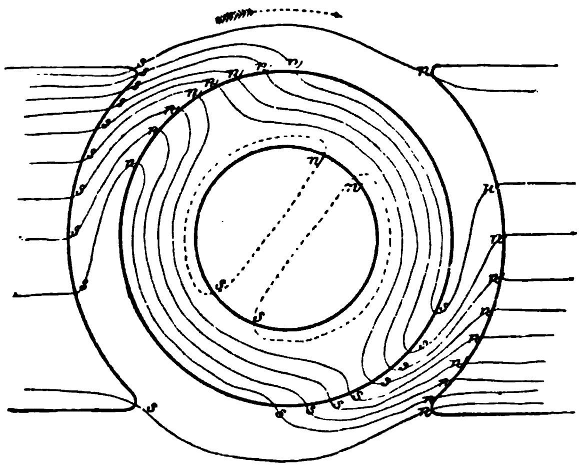


be evident that if we wish to reduce the angle D B A (fig. 191), it can be done by decreasing B C or increasing A B, which in either case would result from making the magnetising force of the field-magnets great as compared with that of the armature. Practice also dictates, for this and for other reasons, that the magnetic field in which the armature revolves should be as strong as possible, and always very much stronger than that developed by the armature itself. Fig. 193 is intended to illustrate roughly the effect on the field of a dynamo when the armature is revolving in the direction indicated by the arrow, and is generating a current. It will be observed that the lines of force *n s*, *n s*, are considerably distorted or dragged out of their normal position (more, in fact, than is the case in actual practice), and that this distortion takes

place in the direction of rotation. The lines which cross the space inside the armature ring indicate the direction of leakage.

When the external resistance through which a dynamo is working is varied, the current in the armature, and therefore the field produced by it, also varies; the same cause may also alter the field produced by the field-magnets if the machine is 'self-exciting,' and consequently in practice the angle of lead sometimes varies considerably. If the effective fields produced by the field-magnets and the armature were varied in the same proportion,

FIG. 193



the angle of lead would remain constant; but we shall see presently that because (among other things) the permeability of and the induction through the field-magnet and armature cores do not vary together, this proportion is not maintained, although the currents producing those fields may be equally increased or diminished. Too much stress cannot be laid upon the necessity for setting the brushes in the proper position, and to facilitate matters they are usually mounted on an insulating rocker so that they may be shifted together through a considerable angle until the correct position is found. When the field is a simple one, such as that

between the two poles of a magnet, and providing it is also uniform, the brushes are placed at opposite extremities of a diameter of the commutator, no matter what the angle of lead may be. When the brushes are not properly adjusted, the coils are short-circuited while they are more or less active, and considerable sparking occurs at the commutator, injuring that important part of the machine, and giving evidence of wasted energy.

Practically the best position of the brushes can be found by shifting them while the machine is running (the external circuit being at the time completed) until there is no sparking observable; and it is found that they must be set even a little further ahead than the point where they are at right angles to the direction of the resultant lines of force. This slight extra lead is necessitated by the rather peculiar and important action which takes place in a coil as it passes a brush. The brush has a sufficiently wide bearing on the commutator to bridge over the interval between the two segments and so to short-circuit the coil attached to them for a brief interval of time; and although this may take place when the coil is in itself, as a generating coil, almost inactive, it must be remembered that it has considerable self-induction, consisting as it does of a number of convolutions of wire wrapped round a comparatively large mass of soft iron. We have already considered at length the reasons which prevent a current being suddenly started or stopped in any circuit which has an appreciable amount of self-induction, from which it is evident that, although the coil itself may not be actually generating any current, yet, just before it passes under the brush, it is carrying the whole of the current generated by the other coils in the same half of the ring. When the coil is thus short-circuited by the brush, the current flowing will not immediately die out, and the extra lead mentioned above is given in order that the coil when short-circuited shall be moving in a field such that the E.M.F. generated will assist in throttling or partially neutralising this current. Hence in order to ensure the entire stoppage of the current, and also even to allow sufficient time for a current in the opposite direction to be just started in the coil before it is actually thrown into circuit again in the other half of the armature, it is advantageous to have the brushes about twice as thick as

a commutator segment, and to give them the slight extra lead above referred to. Independently of this it is impossible in practice to attain the theoretical condition of each coil being absolutely idle even for the briefest possible interval during which the coil might be short-circuited; and although the E.M.F. generated when the coil is least active may be very small, yet the resistance is as a rule so extremely low, being but a small fraction of an ohm, that the current strength when the coil is short-circuited may become considerable. The energy of currents so circulating round the coils while they are in turn short-circuited is expended in heating the wire, and this effect must be remembered as one of the many causes which necessitate special attention being paid to ventilation in designing a dynamo armature. Ventilation does not, of course, prevent the generation of heat and consequent waste of energy, but it facilitates dissipation, and thereby tends to keep the temperature from rising to a dangerous point.

Much can be done to reduce the angle of lead, and minimise sparking, by making the field very strong, and constructing the armature with many sections, each of few convolutions and therefore of comparatively low self-induction. Further, although it involves an increase in the magnetic resistance, and therefore necessitates an increase in the magneto-motive force developed by the field-magnet coils, it is distinctly advantageous, so far as the reduction of sparking is concerned, to design a machine so that the value of **B**, or the intensity of magnetisation in the armature core, shall be considerable, because then the permeability of the iron becomes considerably reduced, and the self-induction of any one coil is much less than it would be if wound over a similar mass of more feebly magnetised iron. In many machines each section consists of but one convolution, and the brushes can easily be adjusted so that absolutely no sparking can be observed, while, the field-magnets being very powerful, the angle of lead is very small, even when the armature is carrying its maximum current. In such a case the armature current may vary considerably without necessitating any readjustment of the brushes, such as becomes necessary with badly designed machines, in which the brushes have to be rocked forward directly the armature

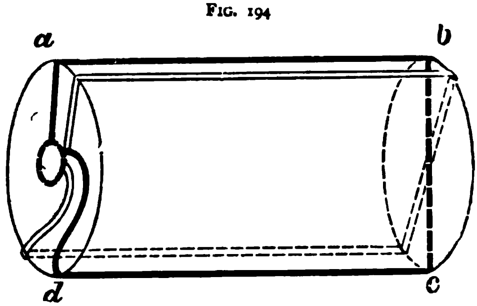
current increases slightly in strength, and backward when it is diminished.

It will be remembered that we commenced the study of the direct-current dynamo with the aid of a simple rectangular coil (fig. 178), but that subsequently, to make the development of the subject easier, a different system of winding was introduced, leading up to the Gramme armature. We are now in a position to comprehend more readily the manner in which excellent armatures, commonly known as 'drum' armatures, are constructed upon the principle of the rectangular coil first mentioned. The drum armature is really a natural development of the shuttle armature. This shuttle armature, consisting, as it does, of only one coil of many turns, the ends of the coil being joined one to each segment of a simple two-part commutator, gives a current fluctuating from maximum to zero or thereabouts, twice in each revolution, and greater steadiness was aimed at and obtained by placing a number of coils symmetrically round the core; in just the same way that a considerable number of coils wound on the Gramme principle yield a more nearly constant current than would result from a single coil or a pair of coils. A drum armature is somewhat more difficult to construct and to illustrate; and although the fundamental principle is in all cases that just indicated, there are many ways of making the necessary connections, some of which will be described when dealing with actual machines.

The general principle may be gathered from fig. 194, where only two adjacent sections are shown, each having one turn. The core is shaped like a cylinder or drum, a commutator, similar to those already described, being mounted at one end of the shaft. From one segment the first coil ascends up to the face of the drum to *a*, thence lengthways along the cylinder to *b*, whence it passes across a chord *b c*, slightly less in length than a diameter, and along the length of the cylinder from *c* to *d*. From *d* it is brought round the face and connected to the segment next to that one to which the other end of the coil is joined. The second coil, shown by open lines for distinction, starts from the segment at which the first coil terminates, and is wound similarly to that coil, being placed a little further round the drum as shown. Its

two ends also are connected to adjacent segments, and, in a similar manner, coils would be placed all round the cylinder, equidistant, and with the ends of each joined to two adjacent commutator segments, so that every segment has two wires connected to it. A reference to fig. 218 will perhaps make this point clearer. Many of the best drum armatures are constructed with but one convolution in each section, but when it is desired to increase this number the wire is simply wound the requisite number of times round the cylinder, and the end of the last convolution led to the commutator segment. Of course, the wires cannot be brought straight across the face, as shown at *b c*, on account of the driving-shaft, and when there are several convolutions in each section care is taken to arrange the wires

FIG. 194



symmetrically round the shaft, so as to preserve a mechanical as well as an electrical balance.

These cross-connections form perhaps the most serious disadvantage pertaining to such drum armatures as compared with ring armatures. In the first place, since portions of all the coils overlap if the connections are made across the face of the drum in the manner indicated in fig. 194, it is possible to get wires having a high potential difference very close together, thus increasing the chance of a breakdown in the insulation ; secondly, if the whole of the end face of the drum is thus covered with wire and insulating material, one of the best points at which ventilation might be effected is blocked up ; and thirdly, it becomes very difficult to repair the armature, as, should any one coil become

defective, it may be found necessary to remove a number of the other coils in order to replace the faulty one.

Many of the improvements in the design of drum armatures consist of devices for overcoming the difficulties caused by these cross-connections, and the modern practice in making these connections will be illustrated in the next chapter.

The great advantage peculiar to a drum armature is the fact that the conductors usefully cut *all* the lines of force passing through the armature core. The only idle wire is that used for connecting the longitudinal or active conductors; and no part of the conductor can generate an E.M.F. in the counter-direction. Consequently, iron or steel may be employed for all the internal fittings; in fact, but for the necessity of allowing space for ventilation, and also for diminishing the weight as much as possible, the whole of the inside of the armature might be occupied by iron. A distinct advantage from a mechanical point of view results from the fact that in a drum armature it is possible to construct the core-plates, spider, and shaft of similar materials which expand and contract to the same extent when the temperature changes; when widely differing materials, such as gunmetal and iron, have to be employed, there is always a tendency to loosen the structure at some point or other on account of the different rates of expansion and contraction.

Since the active limbs, *a b*, *c d*, always cut the lines of the field from opposite sides—viz. one from above, the other from below—the current is induced from front to back in one and from back to front in the other, so that it circulates in the same direction round the coil, precisely as in the case of the simple rectangle first considered.

Each coil is equivalent, then, to two diametrically opposite coils in a Gramme armature, and there will be as many commutator segments as there are coils. The reversal of the current takes place, of course, as each coil passes the zero position—viz. with its plane at right angles to the lines of force—and it is in this position that the segments to which it is connected pass the brush. Also, as in the case of the Gramme ring, the resistance from brush to brush, through two halves of the armature in parallel, is only one quarter of that of the whole armature in series, and,

in calculating E.M.F., the formula $E = \frac{N P n}{10^8}$ holds good, P being the number of active conductors, such as *a b*, round the periphery of the drum.

The drum armature is more efficient than any other form, and its superiority over the ring type may be appreciated by supposing that we have two armatures of equal diameter, and having active conductors arranged round them equal in number and length. The magnetic resistance offered by the drum armature will be the smaller because the quantity of iron in its core is greater, and therefore a given magneto-motive force can urge more lines of force through it than through the ring armature. Further, the whole of the lines passing through the drum armature are usefully cut by the conductors, while, in the case of the ring, some leak across to the shaft and are cut by the inner portions of the wire in such a manner as to reduce the main E.M.F. Therefore, with a given magneto-motive force to maintain the field, the drum armature will give a higher E.M.F. than the ring when they are driven at equal speeds. Equal E.M.F.'s might be obtained by reducing N, the number of lines of force, or P, the number of active conductors; but the factor which it is usually sought to keep as low as possible is *n*, the number of revolutions per second. One great practical advantage of a drum armature is, therefore, that it enables slow-speed machines of comparatively moderate proportions to be constructed, and it will be observed that few slow-speed dynamos have ring armatures; indeed, few simple ring armatures are now used except for the generation of comparatively small currents. Since the proportion of idle wire is somewhat less in the drum than in the ring type, its conductor resistance for the same weight of copper is rather lower.

Having discussed some of the theoretical points involved in the construction and action of direct-current dynamo armatures, we will now consider the methods of maintaining the field, which, it will be remembered, should be as strong as possible. As in the case of the more powerful of the machines described in the preceding chapter, electro-magnets (called the field-magnets) are employed for this purpose. Practical difficulties and efforts to

secure economy in construction somewhat influence the shape, but in every case the great object should be borne in mind—viz. the necessity for leading as many lines of force as possible through the space between the poles, in which the armature is made to revolve.

The magneto-motive force, which sets up and maintains the field, is obtained by means of a current passing through one or more coils of wire, and is proportional to the strength of the current flowing and the number of turns of wire in the coil, as has already been fully explained (Chapter VII.), and the quantity represented by the product of these two factors is referred to as the 'ampere-turns.'

Now, for any given machine, the number of lines of force which must be urged through the armature is usually determined beforehand, but as with every electro-magnet, of whatever design, there is a certain amount of 'leakage,' only a portion of the lines generated by the field-magnet pass through the armature.

But power is expended in the generation and maintenance of the lines of force, and those which are rendered useless by leakage represent so much power wasted. It is obviously advisable that this waste should be reduced to a minimum, and the greatest possible proportion of the lines developed led through the armature. This may be accomplished by making the magnetic resistance of the desired path very low. The whole magnetic circuit should, preferably, approximate to the circular form, and whatever the quality of the iron employed, its sectional area must be sufficient at every point to prevent the magnetic induction being so high as to greatly reduce the permeability of the iron. We have mentioned one advantage which results from working the armature core at a rather high induction, but in doing this we cannot, of course, avoid correspondingly increasing the magnetic resistance of the circuit.

The spaces between the pole-pieces of the field-magnet and the core of the armature offer considerable magnetic resistance, which may be taken as proportional to the distance between the iron surfaces, the permeability of the copper wire and its insulation being to all intents and purposes the same as that of air. The only way of diminishing this high resistance is to reduce the

distance between the iron surfaces as much as safety will permit, and, since this minimum distance is nearly the same in machines of all sizes, we see one reason to account for the observed fact that small dynamos are generally less efficient than larger ones.

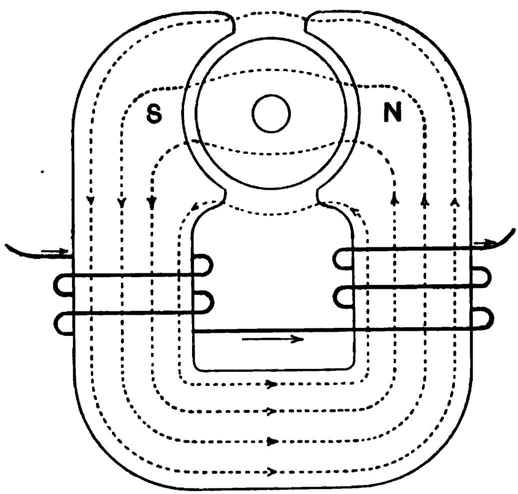
In estimating the tendency to leakage it must not be forgotten that while the permeability of iron decreases with an increase of the magnetic induction through it, that of air remains constant, and the difference between the permeability of the nearly saturated iron of the field-magnets and that of the air space is never so great as the difference usually given for unsaturated soft iron and air.

Two very important considerations influencing the design of field-magnets are economy in construction and mechanical strength; and in practice, as we shall see, it is sometimes considered advisable, where the question of weight is unimportant, to use cast iron for part or all of the field-magnet core. It is preferable to forge or cast the core in one piece, as joints break the molecular continuity and increase the magnetic resistance considerably, although this disadvantage can be minimised by making the surfaces in contact fit truly. The principal practical objection to the use of cast iron is that, since its sectional area must be at least twice that of wrought iron, a much greater quantity of copper is required to form the field-magnet coils. Copper is expensive, while cast-iron cores are far less costly than equivalent ones of wrought iron, and the student should observe how different makers aim at true economy in this matter. Even leaving out the question of cost and weight, it does not by any means follow (as is sometimes supposed) that a dynamo properly designed to perform certain work, and having cast iron in its construction, is inferior to one built wholly of wrought iron to perform the same work. Steel is now employed in many cases instead of wrought iron for field-magnet cores, the principal advantage in its favour being that it can be cast into the desired shape, thus avoiding the somewhat expensive processes of forging and machining up to shape, which are necessary in the case of wrought iron. Ordinary hard tool-steel is, of course, unsuitable for this purpose, the material employed being mild steel, which contains very little carbon, and cannot be hardened or tempered, and the most suitable qualities of which,

when carefully annealed, are scarcely inferior to wrought iron as regards permeability.

The composition of the 'ampere-turns'—that is, the proportion of current strength to the number of convolutions—will depend largely upon the manner in which the exciting current is obtained; for it is sometimes necessary to have considerable resistance in the coils, and then the number of convolutions may be made great and the current correspondingly weak; while in other cases a high resistance is inadmissible, when only a few turns

FIG. 195



can be employed, and the necessary magneto-motive force must then be obtained by the aid of a heavy current.

When the exciting current is obtained from an entirely separate source—for example, from a secondary battery or another dynamo—the machine is termed a 'separately excited' dynamo. Such an arrangement is illustrated in fig. 195, where S N are the pole-pieces of a massive horseshoe-shaped electro-magnet, the armature, indicated by two concentric circles, being placed in the space between the pole-faces. A few turns of wire representing

the field-magnet coils are shown round the limbs of the field-magnet, and if a current be sent round these convolutions in the direction indicated by the arrows the field-magnet will become magnetised, the direction of the lines of force being as shown by the dotted lines. Some of these lines of force may fail to pass through the armature, as indicated in the figure, where lines are shown leaking across between the pole-tips above and below the armature; but if the space between the surface of the armature core and the pole-faces be small, if the pole-tips do not approach too closely, and if there be sufficient iron in the armature core, the great majority of the lines of force will take the desired path, and a considerable E.M.F. can then be developed by rotating the armature.

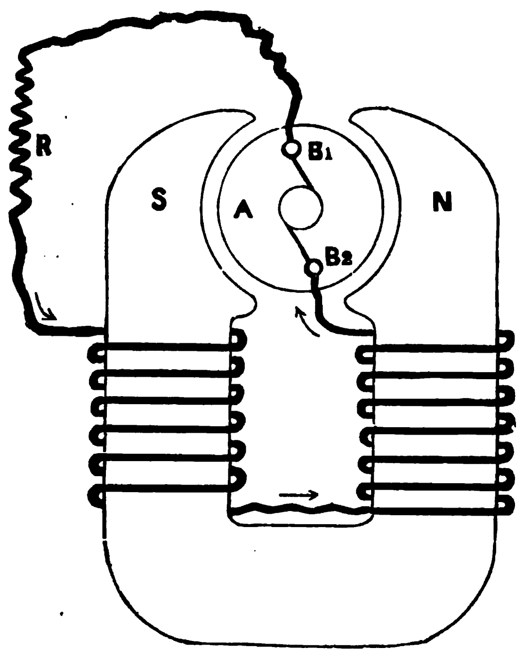
A separately excited machine possesses some advantages, on account of the fact that the exciting current is at all times entirely independent of the E.M.F. or current developed by its own armature; but these machines are only used in special cases, because of the inconvenience in providing a separate source of current for the field-magnet coils.

At the beginning of this chapter we referred to a very important benefit following the commutation of the current—viz. the possibility of using all or part of the current generated in the armature of any machine for the purpose of magnetising the field-magnets of that same machine, and the simplest method of doing this, in which the whole of the current is so employed, is exemplified in fig. 196. A machine having its connections made in the manner there shown is known as a 'Series' dynamo.

As in the case of fig. 195, S N are the pole-pieces of a massive horseshoe electro-magnet; the armature A revolves in the space between them, B_1 B_2 being the brushes which press against the commutator, and by means of which the current generated in the armature can be led to any desired point. In this case, one end of the wire forming the coil of the field-magnet is connected directly to the brush B_2, the other end being joined through the external circuit R to the opposite brush B_1, so that the circuit of the field-magnet is completed through the armature coils. Hence the whole of the current generated in the armature must pass round the coils and magnetise the electro-magnet.

But how is the current to be started in the first instance? It so happens that even the purest soft iron is found to retain *some* of the magnetism imparted to it, and therefore the massive cores of a dynamo, having once been strongly magnetised, always retain an appreciable amount. This 'residual' magnetism is sufficient to project a few lines of force through the armature coils; so that, when the armature is rotated, a feeble current is generated

FIG. 196



therein. The connections being made as in fig. 196, this current leaves the armature by the top brush B_1, flows through the external circuit, and, returning to the machine, passes round the coils of the field-magnets, the circuit being completed through the lower brush B_2. The feeble current sent in this way through the field-magnets has the effect, providing that its direction round the magnets is such as to set up lines of force in the same direc-

tion as those of the residual magnetism, of increasing the strength of the field in which the armature rotates, and, consequently, the current generated also becomes stronger. This further increases the magnetic field developed, and, consequently, also the current strength; action and reaction succeeding one another in this manner until presently the current becomes very strong indeed. This increase does not, however, continue indefinitely, there being two especially important restrictions which tend to fix a limit to the current produced. In the first place, although the core of the field-magnet may be very massive, its magnetisation eventually approaches the saturation-point, beyond which an increase of the current in the coils would not by any means involve a corresponding increase in the strength of the effective field. Secondly, the rotation of the armature, although performed with little effort at the commencement, requires a considerable expenditure of energy as the strength of the current increases. We are even able to estimate the relative power required to turn the armature while currents of different strengths are being generated. For our present purpose the calculation can be made very simple by ignoring the power lost in mechanical friction, &c. The electrical power which is being developed in any circuit can be found by simply multiplying together the electro-motive force in volts and the current strength in amperes in that circuit, the result being the number of watts of power developed therein, or $W = E \times C$, W being the number of watts; or, since the E.M.F. is equal to the product of current strength and resistance (that is, $E = C \times R$), we may write $W = (C \times R) \times C = C^2 \times R$; that is to say, the power in watts developed is equal to the resistance in ohms multiplied by the square of the current strength in amperes.

As the resistance of the dynamo armature and magnet coils is usually known, only one measurement, that of current strength, need be taken, which can be done by any ammeter of negligibly low resistance.

Supposing, for example, the resistance of the armature to be 3 ohms, and that of the field-magnets to be 2 ohms, then the total resistance is 5 ohms. When a current of 10 amperes is generated without any external resistance, the electrical power appearing in the circuit is equal to $C^2 R = 100 \times 5 = 500$ watts; and if the

current is increased to 20 amperes, then $C^2 R = 400 \times 5 = 2000$ watts.

Now, in both cases at least as much mechanical power is required to turn the armature as appears in the circuit as electrical power. Indeed, a certain amount in excess is necessary (depending upon the efficiency of the machine), because some energy must be wasted in overcoming the mechanical friction of the bearings, &c., and still more by various electrical causes, such as eddy currents and the currents which flow in the armature coils during the period of short-circuiting.

The main point, however, upon which we desire at present to lay stress is that the increase in current is not, and never can be, obtained without a corresponding increase in the power expended in turning the armature; in fact, from the above reasoning it is clear that in a series dynamo such as the one described, the mechanical power expended varies as the *square* of the strength of the current obtained in the external circuit, always supposing the resistance of the circuit to remain constant, and ignoring the mechanical power lost in the machine during conversion.

The ultimate strength of the current is, then, limited not only by the saturation of the field-magnets, but also by the amount of power at our disposal to drive the armature round. The engine, or other source from which the power is derived, must at least be able to furnish power equal to the maximum electrical power it is desired to obtain, to which must also be added that which is wasted or lost in the conversion. A yet further limit is imposed by the limited capacity of the conductors for carrying heavy currents.

With regard to the residual magnetism which is relied upon to start the current, it may be remarked that if the field-magnets are once strongly magnetised by a current passing in the direction in which it is desired the currents shall afterwards be generated, the cores will rarely lose all traces of magnetisation, especially if of cast iron. This sometimes happens, however, when the dynamo is moved, and the magnetism may even be reversed; but matters can easily be righted by passing a current, say, from a few primary or secondary cells for a moment in the proper direction through the field-magnet coils.

Hitherto we have considered the dynamo as working on 'short circuit'—that is, with the circuit completed without the introduction of any appreciable external resistance. In practice, however, we require the current to do a greater or less amount of work in an external circuit, such as developing light in electric lamps or driving an electric motor. In such a case, only a small part of the power is expended in overcoming the internal resistance (that is, the resistance of the armature and field-magnets) and maintaining the field, the remainder being employed in the external circuit. It is easy to find the relative amount of power absorbed in the two parts of the circuit. Thus, suppose the strength of the current to be 40 amperes, and the total E.M.F. to be 80 volts, then the total electrical power developed is $40 \times 80 = 3200$ watts. If, now, the difference of potential between the two extremities of the external circuit is found to be 75 volts, the power absorbed therein is $40 \times 75 = 3000$ watts, for the strength of the current is the same in all parts of the same circuit. The remaining difference of potential is $80 - 75 = 5$ volts, which is the fall along the internal circuit; the internal circuit absorbs, therefore, $40 \times 5 = 200$ watts. In this way, the ratio between the power spent in the external and internal portions of the circuit can in every case be measured.

The two ends of the external circuit above referred to are connected to the 'dynamo terminals,' and the potential difference thereat can be measured by any suitable voltmeter. Since, also, the power spent in either portion can be calculated by multiplying the square of the current strength by the resistance of that portion of the circuit, and as the current is the same in each part, it follows that the energy absorbed in either part is directly proportional to the resistance of that part. Thus, if the resistance of the external circuit is R ohms, and that of the dynamo r ohms, the total resistance is $\mathrm{R} + r$. Let the total number of watts developed be W. Then, denoting the watts absorbed in the internal and external parts of the circuit by x and y respectively, we have

$$x : y :: r : \mathrm{R},$$
$$x : \mathrm{W} :: r : \mathrm{R} + r,$$
$$y : \mathrm{W} :: \mathrm{R} : \mathrm{R} + r.$$

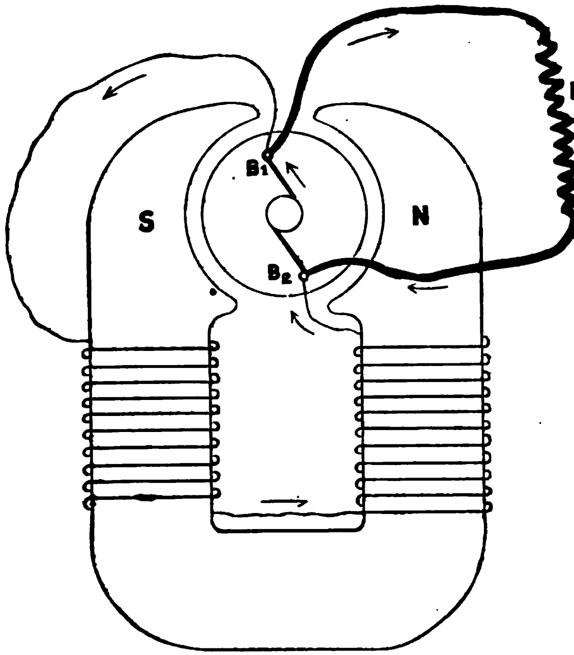
But it very rarely happens that any dynamo works through an external circuit of constant resistance; if it is supplying current to electric lamps, some of them are liable to be thrown into or out of circuit at any moment, and the behaviour of a series dynamo under these varying conditions must be briefly noted. Supposing the lamps to be joined up in series, then any addition to the number will increase the external resistance and reduce the current strength, and this means a corresponding decrease in the strength of the field, and, consequently, a further diminution in the current strength. If we suppose the lamps to be joined up in parallel, then any addition to the number in circuit decreases the total resistance and increases the current. This, by strengthening the field, still further increases the current strength even beyond that actually required. So that in either case considerable difficulties arise when a series dynamo is used on a circuit of varying resistance.

Moreover, this variation of the current, while it varies the effective fields of the armature and field-magnet, does not do so in the same proportion. The angle of lead must therefore be altered for every considerable alteration of the current, or injurious sparking at the brushes will ensue. A series dynamo can be used most conveniently in cases where a current of constant strength is required, and then if the resistance of the circuit remains constant the current also remains constant, provided the dynamo be driven at a regular speed. Should the resistance of the external circuit vary from time to time, the current can still be kept constant by varying the speed or by providing an arrangement to automatically vary the strength of the field in which the armature rotates. For example, the field-magnet coil may be shunted by a resistance whose value can be reduced, and so shunt a larger proportion of the current from the field-magnet coils, whenever the current in the main circuit tends to rise above the standard strength; and increased so as to shunt less current when the main current falls below its proper value.

It will be evident, however, that the conditions under which the simple series dynamo can be conveniently employed are somewhat limited. For general work, and especially in cases where a constant potential difference and not a constant current is

required to be maintained, some better method of 'regulation' is essential—that is, some arrangement by which the machine shall be made to develop just as much electrical power as the variations in the external circuit demand from it. The first approximation thereto is obtained by an alteration in the manner of winding, giving us what is known as the 'Shunt' dynamo.

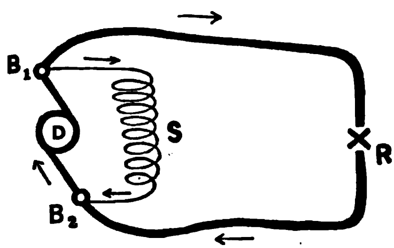
FIG. 197



In the shunt dynamo the field-magnet coils, instead of being joined up in series with the armature and external circuit, are so connected that they form a 'shunt' *to the external circuit*, and receive, therefore, only a part of the current generated in the armature, the proportion depending upon the relative resistances of the external circuit and the shunt coils. Fig. 197 shows the manner in which the connections are made, and the principle,

which is very simple, should be readily grasped. The armature is rotated between the pole-pieces, and a certain E.M.F. is developed in the usual manner. The whole of the current generated passes, as a matter of course, through the armature, and we will suppose that its direction in both halves of the armature is upwards, or from the lower to the upper brush. At the upper brush, B_1, the circuit is divided, two paths being open to the current: one round the coils of the field-magnets, by taking which it augments and maintains the field; and the other through the external circuit R, where it can be used for lighting purposes, or to perform such other work as may be required. Both of these paths, however, terminate at the lower brush, B_2, and the strength of the current which goes round either path is, as we have just indicated, simply inversely proportional to the resistance of that path. To assist in overcoming any difficulty which might be experienced in understanding the connections or in tracing the path of the current in the various branches, the arrangement is shown even more clearly in fig. 198, R being the external circuit. S the field-magnet coil, B_1 B_2 the brushes, and D the commutator of the dynamo.

FIG. 198



The method of measurement applied to the series dynamo can also be adopted with the shunt machine, for the amount of power absorbed in the armature, field-magnet coils, and external circuit respectively, can be found by multiplying the current in each particular part of the circuit by the potential difference at its extremities. The armature resistance must be very low, otherwise, as it carries the whole of the current, the power absorbed therein becomes considerable; on the other hand, the resistance of the field-magnet coils requires to be relatively high.

In an actual machine giving good results, the resistance of the armature is a trifle less than one-hundredth of an ohm, while the magnet coils offer 16·93", or about 1700 times as great a

resistance. Supposing this machine were driven at such a speed as to develop a potential difference at the brushes of 100 volts, the external resistance R (consisting of a number of lamps in parallel) being half an ohm, then the current in the external circuit would be 200 amperes, and the power usefully employed therein $100 \times 200 = 20{,}000$ watts. The resistance of the shunt coils being 16·93", and the potential difference at the extremities also 100 volts, the current produced therein will be almost 6 amperes. So that $6 \times 100 = 600$ watts will be absorbed in maintaining the field. The current in the armature of a shunt dynamo is the sum of the currents in the two external branches, viz. the field-magnet coils, and the external circuit, and in this particular case it is $6 + 200 = 206$ amperes. The armature resistance is 0·01", and since the fall of potential along it is equal to the product of current strength and resistance, the fall of potential along the armature from brush to brush is $206 \times 0{\cdot}01 = 2{\cdot}06$ volts. Therefore the power absorbed in it is $2{\cdot}06 \times 206 = 424{\cdot}36$ watts, which result, of course, might also be obtained by multiplying together the square of the current passing through the armature, and the resistance. Now the whole electrical power developed is 21,024 watts, of which number 1024 are absorbed in maintaining the field and in overcoming the armature resistance, the remaining 20,000 being usefully expended in the external circuit.

The ratio of the power usefully available to the total power developed is commonly known as the 'electrical efficiency' of the dynamo, and in the case just considered this ratio is $\frac{20{,}000}{21{,}024}$, or the electrical efficiency is slightly over 95 per cent. It is hardly necessary to point out that a very slight increase of the armature resistance would considerably lower this figure, because the armature carries such a heavy current. The electrical efficiency would, on the contrary, be slightly increased if more turns of wire were wound on the field-magnet, because the added resistance would diminish the current strength, although the magneto-motive force would remain unaltered, since the increase in the number of turns would just balance the reduction of the current. Similarly, the strength of the field would be practically unaltered if, say, half the number of convolutions were removed from the field-magnet

coil, because, the wire being of uniform resistance throughout, the removal of half of it would halve the resistance of, and double the current strength in, the field-magnet coil, supposing the potential difference of 100 volts to be maintained in both cases. The efficiency would, however, be lowered by such a procedure, because twice as much energy would be wasted in heating the field-magnet coils, the energy so wasted being proportionate to $C^2 R$.

Ignoring for the moment the small amount of residual magnetism, it will be observed that in a series dynamo the field-magnets become demagnetised immediately the external circuit is broken, because the whole of the current is then stopped. In the case of a shunt dynamo, however, if the external circuit R in fig. 198 is broken, there is an alternative path left for the current generated by the armature, viz. round the field-magnet coil S. Although under these circumstances the current passing through the armature is less than when the external circuit is completed, yet, since the armature reaction and the fall of potential in the armature are less, the terminal pressure is higher, and consequently the current in the field-magnet coil is increased; hence the strength of the field due to the field-magnet is always at its maximum when the external circuit is disconnected; or exactly opposite to the case of a series dynamo. In the latter machine the most powerful current is generated and the field is strongest when the terminals are joined by a piece of thick wire; but this proceeding would have the reverse effect upon a shunt machine, because practically no current would then flow round the field coils on account of the very low resistance of the alternate path.

Although the shunt dynamo (especially if the resistance of its armature is low) is through a certain range less affected by changes in the external circuit than the series dynamo, neither of them is, for many purposes, sufficiently 'self-regulating,' or able to accommodate itself to these external variations. We may require a dynamo to do one of two things: either (*a*) to regulate itself so as to send a *constant current*, or a current of uniform strength, through the external circuit, although the resistance may be considerably varied; or (*b*) we may require it to maintain a *constant potential difference* at the extremities of the external circuit—that is,

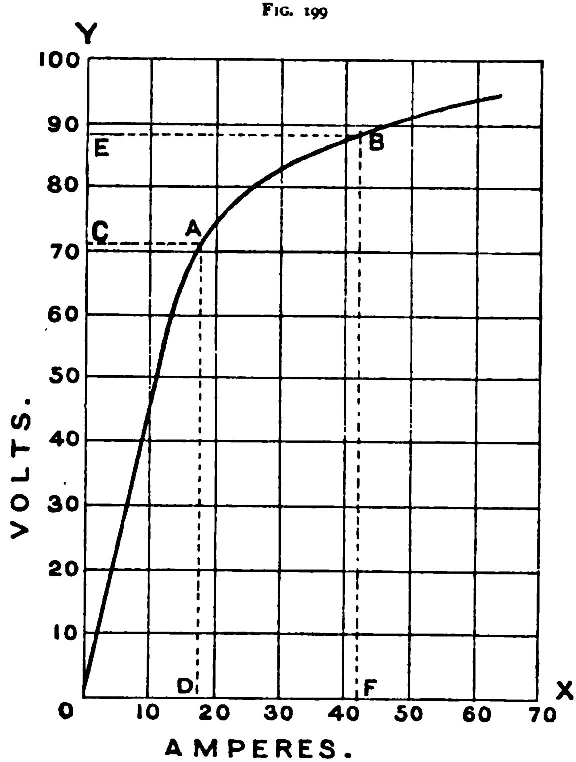
at the dynamo terminals—under like variations of resistance. No one machine can be constructed to fulfil both these requirements, and we will now consider the best of the many methods of automatically maintaining a constant potential. This consists in the combination, in one machine, of the series and the shunt methods of winding. The simplest way, perhaps, of viewing the arrangement, is to consider the machine as a shunt-wound one, having added to it, round the magnet-limbs, a few turns of wire in series with the external circuit. Then, when the external resistance is made very low, and, as a consequence, the conditions are set up for the current in the shunt coils to be reduced almost to nothing, the magnetic effect of the series coils becomes a maximum, on account of the increase in the strength of the current which flows through those coils, so that the opposite variations in these two sets of coils tend to keep the field more or less constant. It is clear that the success attending this combination will depend largely upon the proper proportions being given to the shunt and series coils, and in order to ascertain what these proportions are or should be for any particular case, we will now introduce a convenient method by which the variation of the E.M.F. developed by a dynamo under varying conditions can be studied.

Let us start with the case of a series machine, driven throughout the experiments at a constant speed, and joined up to a set of suitable known resistances which can be varied as desired. The resulting current can be measured by any suitable ammeter, and, the resistance of the machine and of the external circuit being known, the whole of the E.M.F. developed can be calculated as the product of amperes and ohms. We thus obtain the amperes of current flowing and the whole of the volts of E.M.F. developed, and these two quantities may be similarly found for any number of values which we choose to give the external resistance.

For instance, we might start with the external resistance very high and reduce it by suitable gradations until it becomes as low as safety to the machine will allow. A table might then be made showing the number of amperes flowing at every stage and the volts corresponding thereto. But by means of the 'squared paper' previously referred to, the results of all these experiments can be shown graphically in the form of a curve, known as the

'characteristic curve' of the particular machine experimented with. Fig. 199 represents such a curve, taken from a series machine, driven at a constant speed. The volts calculated are measured off in vertical distances or ordinates, and the amperes in horizontal distances or abscissæ, the intersection of *corresponding* ordinates

FIG. 199



and abscissæ being points on the curve. The length of the side of a square in the figure represents 10 volts or 10 amperes, but in practice it is better to use a larger sheet of paper divided into a greater number of squares, one side of each square representing 1 volt, or 1 ampere as the case may be. One of the

experiments with this machine showed that 70·6 volts were developed when 18·2 amperes were flowing, and the point A on the curve is the result of this particular experiment. It is the point of intersection of the two straight lines, C A and D A, drawn at right angles to O Y and O X respectively, C A being 18·2 units and D A 70·6 units in length (the unit being one-tenth of a side of one of the squares). Another experiment, which determined the position of the point B, showed that 42 amperes were flowing when 87·4 volts were developed; therefore the distance E B is made equal to 42 units, and F B to 87·4 units. Other points were fixed by similar experiments, and by joining these points together the curve was obtained. In the region of any decided change in the curvature the number of experiments must, in order to ensure a correct curve, be greater than they need be in the more uniform portions of the line. Notwithstanding, however, the exercise of the greatest possible care, some of the points are usually placed a little out of position, owing to experimental error. But experience and theory teach us that zigzag deviations should never appear in the curves of dynamo machines, so that when the points do not lie exactly on a regular curve, we can, to a certain extent, correct experimental errors, by striking what may be called an average, with the aid of a flexible ruler.

Were the amperes and volts to increase in the same proportion throughout, the 'curve' would be a straight line; but with every self-exciting series dynamo we get a curve somewhat similar to the one here given—that is to say, with the first part ascending rapidly, then a decided bend, followed by a fairly straight portion making a smaller angle with the horizontal. It has already been pointed out that although the E.M.F. rises as the current flowing round the field-magnets (and, therefore, as the strength of the field) increases, a stage is reached when a given increase in the current does not give a proportionate increase in the field. This happens when the iron in the field-magnets is becoming saturated, and it is at this stage that the decided bend in the characteristic curve shows that the amperes are increasing faster than the volts. The student will probably notice the general likeness between this curve and those given in Chapter VIII. for the magnetisation of soft iron. In fact, the experiments here referred to constitute a very rough

method of constructing the magnetisation curve for the iron of the field-magnet core, because the magnetising force is proportional to the current strength, and the magnetic induction varies approximately as the strength of the field projected through the armature, of which strength the value of the E.M.F. is a more or less accurate measure.

It sometimes happens that by merely glancing at a curve we can criticise the design of a machine in some important respects; for instance, the effect of having too little iron in a machine would be to make the bend occur earlier than it really should do. Other points of criticism will manifest themselves presently.

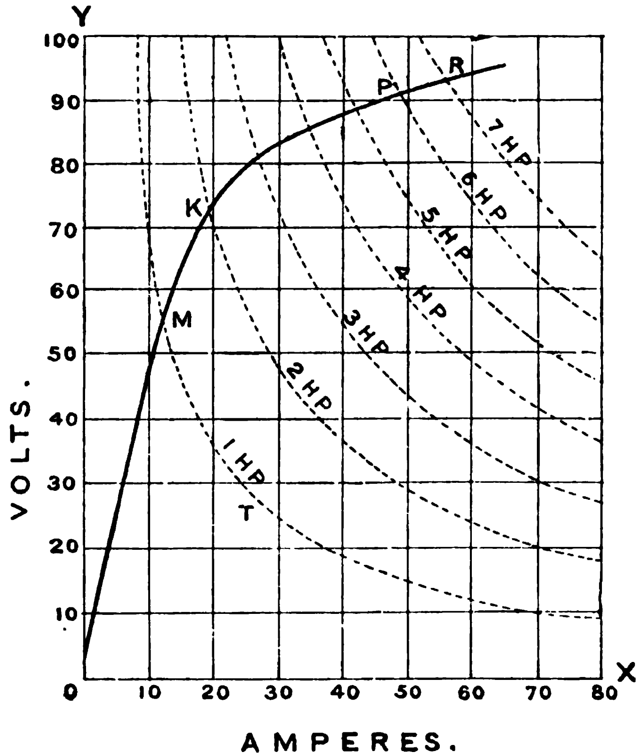
Reverting to fig. 199, it will be seen that the curve commences not exactly at the point O, but at a point a little way up the vertical line, thus apparently indicating the existence of a small E.M.F. before the current commences to flow. This actually is the case, and results from the existence, in the field-magnets, of residual magnetism, which provides a weak field and produces a small potential difference at the terminals before the circuit is completed.

The two quantities—current and E.M.F.—plotted in this curve, are those which, when multiplied together, enable us to estimate the amount of power being developed in the whole circuit; for the product of one volt and one ampere is one watt, which is the electrical unit of power, or rate of expenditure of energy, and 746 watts correspond to one horse-power. It follows that we can select any point on the curve and readily calculate what power was being developed in the circuit at the particular moment that that point was determined; for instance, during the experiment which determined the position of the point A, the power developed was $70{\cdot}6 \times 18{\cdot}2 = 1285$ watts $= 1{\cdot}72$ horse-power.

Such calculations can, in a measure, be avoided by the addition of another set of curves cutting the characteristic at points which correspond to a certain horse-power or fraction of a horse-power. Fig. 200 is a copy of fig. 199, with a number of these horse-power curves added in dotted lines. At the point M, where the characteristic cuts the 1 H.P. line, the product of volts and amperes is equal to 746 watts, while at K it is equal to $2 \times 746 = 1492$ watts. These curves are also of service in readily show-

ing the manner in which the power developed by a machine varies when the speed, E.M.F., and current are all subject to change. For example, if the dynamo with which the characteristic curve under notice was obtained were driven at a higher speed, the E.M.F. for

FIG. 200

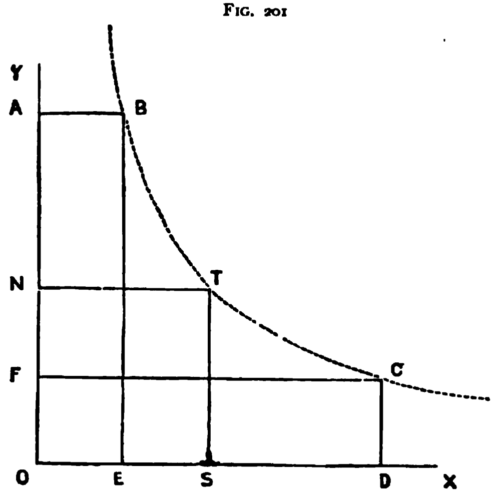


a given current would be greater—that is, the vertical distances will be relatively greater than the horizontal ones as the speed is increased and a curve somewhat similar in shape, but placed above the existing one, will be obtained. Several curves obtained with different speeds may thus be plotted on the same sheet of paper,

and the power developed at different stages in each case readily compared, by reference to the horse-power lines.

These horse-power lines may be constructed by a simple, although somewhat tedious, process. As an example let us take the 1 H.P. line in fig. 200; T, the nearest point to O, will be equally distant from O X and O Y—that is to say, the perpendiculars drawn from T to O X and O Y will be equal. These perpendiculars are shown in fig. 201, where T S = T N; and their product T S × T N must be equal to 746 units, since T is a point on the curve.

FIG. 201



Now N T S O is a square, all the sides are equal, and therefore $TS \times TN = TN^2 = ON^2 = 746$, or $ON = \sqrt{746}$. (The unit in fig. 200 is one-tenth of the side of a square, and in every case the unit is that length taken to represent one volt or one ampere.) If, therefore, we take O N and O S equal to $\sqrt{746}$—that is, 27·3 units in length—and draw perpendiculars from N and S, their intersection in T will give the first point on the curve. Then, if any convenient number of rectangles, equal in area to the square, be constructed, the product of two adjacent sides will equal $ON \times TN = 746$. For instance, the rectangles O B and O C are equal to the square

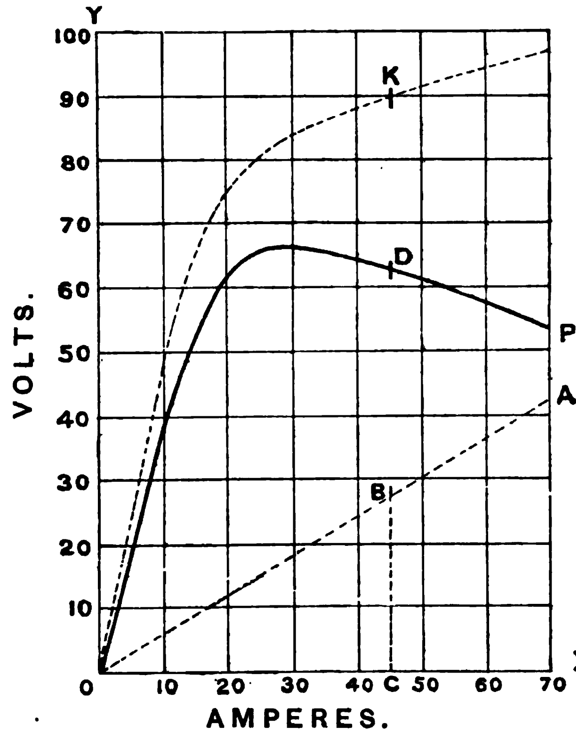
O T (O A and O D being each twice the length of O N, and O F and O E being half that length). Therefore, since A B × B E and C D × C F are each equal to 746, B and C are points on the curve. This method illustrates the principle in a simple manner, and quicker methods of finding pairs of lines whose products are equal will suggest themselves (Euclid, III. 36). The side of the square determining the first point on the 2 H.P. line will be equal to $\sqrt{(2 \times 746)} = \sqrt{1492}$; consequently the other points can be found in the same way as before.

It will be remembered that the characteristic in fig. 199 was constructed by measuring the amperes, and calculating the total volts; but it is more convenient to join up a voltmeter and measure directly the volts *at the terminals* of the dynamo, and then plot a curve showing the potential difference at the terminals (instead of the total E.M.F.), corresponding to various values of the current. In fact, this latter curve, usually called the external characteristic curve, is the more useful of the two, for in practice it is the external potential difference which concerns us most.

In fig. 202 the curve O P is the *external* characteristic, obtained from the same machine as the previous curve, running at the same speed. The bend is now even more clearly defined; in fact, after a certain point the potential difference falls as the current is increased. One reason for this bending down is, as we have said, the magnetic saturation of the iron; it is also partly caused by the heavy current in the armature and the fall of pressure consequent upon the resistance of the armature winding. The curve shows us then, at a glance, the particular current strength at which we can get the maximum external potential difference at a given speed, and, of course, by inserting the horse-power lines, we can also see the amount of power absorbed in the external circuit. Now the remainder of the E.M.F is absorbed in overcoming this resistance of the armature, and since the armature resistance is constant, this portion of the E.M.F. (found by multiplying the armature resistance and the current) will always be proportional to the current flowing. In fact, if we plot the 'curve' for current and E.M.F. expended in the armature, we get the straight line O A. And further, if at any point, say C, we add together the vertical distance from the base line to the line O A, and

the vertical distance to the external characteristic—that is to say, if we add together C B and C D—we get a line proportional to the E.M.F., giving the point K on the original total characteristic. In this manner we can construct the total characteristic curve, now

FIG. 202



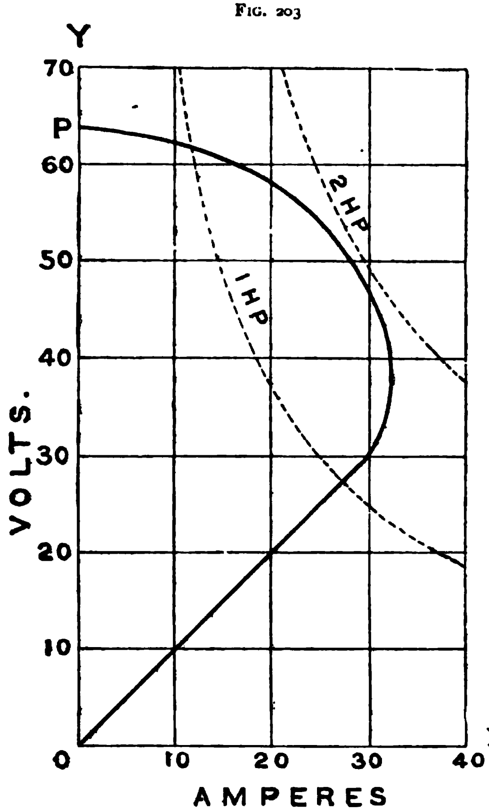
shown as a dotted line; or, given this curve, we might draw the line O A, and, by subtracting, deduce the external characteristic.

The greater the armature resistance the greater will be the fall of potential along it for any given current strength, and therefore also the greater will be the angle which O A makes with the

horizontal. In fact, the tangent of this angle is proportional to the armature resistance, for $R = \frac{E}{C} = \frac{BC}{OC} = \tan BOC$.

If this angle happened to be 45°, we should know that the armature resistance is 1 ohm, for the tangent of 45° is 1. In the

FIG. 203



present case the angle is 31°, the tangent of which is 0·601; therefore the armature resistance is 0·601 ohm.

The 'external' characteristic for a shunt-wound dynamo is very different, as will be seen on referring to fig. 203, which is the

curve obtained from a shunt machine, the vertical distances being proportional to the potential difference at the terminals, and the horizontal distances to the current in the external circuit. As before, the scale taken is such that a side of a square represents 10 volts or 10 amperes, as the case may be. If we suppose the series of measurements to be commenced when the external circuit is disconnected, and its resistance therefore infinite, the potential difference at the terminals of the machine will then have its maximum value, and we shall obtain P, the highest point on the curve. With this particular machine running at a certain constant speed, the maximum potential difference happened to be 63·5 volts, and as, of course, no current could flow in the external circuit, the point P is placed on the line O Y, at a distance of 63·5 units above O X. When very high resistance is introduced, so as to allow just a feeble current to flow in the external circuit, the potential difference at the terminals falls slightly, and continues to fall as the resistance is reduced and the current consequently increased. At first the amount of current abstracted from the field-magnet coil makes but little difference to the strength of the field, and therefore the potential difference falls but slightly. But when the external resistance is so low that the current becomes about 20 amperes, the amount abstracted from the shunt begins to have a very decided effect upon the strength of the field. The potential difference at the terminals or brushes then falls considerably, and, the current remaining fairly constant during a small range, the effect is seen in the curve as a sudden bend downwards—almost, in fact, a perpendicular line. The resistance being still further reduced, not only does the potential difference fall, but also the current, giving the curve a turn *backwards*, until presently the field-magnets lose their magnetism, and when the terminals are short-circuited the curve terminates in the point O, potential difference and current being then reduced to *nil*. As the field-magnets, however, rarely lose the whole of their magnetism, a feeble current usually continues to flow after the terminals have been short-circuited, so that the curve may really end at a point some little distance from O along the line O X.

This curve was obtained from a machine of early design, and it would not by any means be considered a satisfactory result at

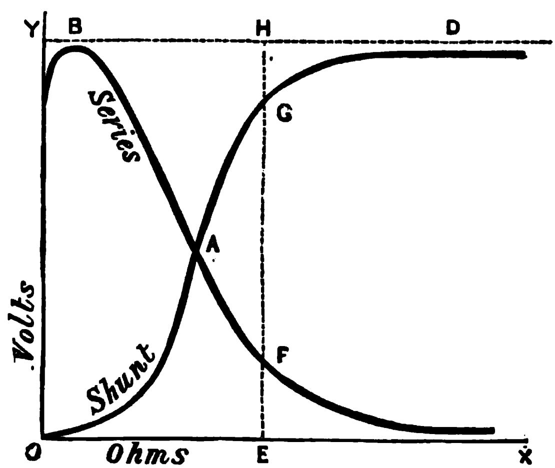
the present time. It is retained, however, because it shows the effect of defective design more clearly than would a curve obtained from a modern shunt dynamo. The sudden drop in the potential difference at the brushes is due chiefly to the armature resistance being too high and the field-magnets not being sufficiently powerful. Both of these defects show up more decidedly as the armature current is increased, and the effect of the armature field on a feeble field due to the field-magnets has already been dealt with. Excessive resistance in the armature not only causes a great loss of power therein, but it renders the maintenance of even an approximately constant potential at the brushes impossible unless either the speed of rotation or the strength of the field be increased with the increase of current taken from the machine. Suppose, for example, a shunt-wound machine, driven at a constant speed throughout, develops an external potential difference of 100 volts when the external circuit is open or disconnected. This will be almost equal to the total electro-motive force developed by the machine, since the current then flowing through the armature—viz. that taken by the shunt coils—will in any case be so small as to make the fall of potential along the armature inconsiderable. If now the external circuit be closed through a comparatively low resistance, the potential difference at the brushes will fall, and the extent of the fall will largely depend upon the value of the armature resistance. Suppose, for example, the armature resistance to be as high as 0·5 ohm, and the resistance of the external circuit to be also 0·5 ohm, the fall of potential along the armature will be equal to that in the external circuit; and since the total E.M.F. developed cannot exceed that developed before the external circuit was closed, the potential difference at the brushes cannot possibly exceed 50 volts. As a matter of fact, the potential difference will be considerably less than 50 volts, because the value of the current passing through the field-magnet coils depends upon the potential difference at the brushes; and when this is reduced the current through the shunt coils, and therefore also the strength of the field and the total E.M.F. developed, will be correspondingly reduced. If, on the other hand, the armature resistance were but one-hundredth of an ohm, not only would the current strength with a total E.M.F. of 100 volts be much greater,

but the fall of potential along the armature would now be rather less than two volts, leaving rather more than 98 volts potential difference at the brushes, and this small drop would not greatly affect the strength of the field. In fact, were it possible to construct an armature with absolutely no resistance, there would (neglecting for the moment the distortion of the field by the armature current) be no fall of potential along the armature at all, and the total E.M.F. developed would be available at the brushes, whatever the strength of the current might be. Such a result is of course unattainable, but very good shunt machines are now frequently constructed with a powerful field and an armature of very low resistance; and the slight regulation which is then required in order to maintain a constant potential difference at the brushes is effected by means of a set of resistance coils placed in series with the shunt or field-magnet winding. When the external resistance is considerably lowered, thus increasing the current strength and tending to lower the potential difference at the brushes, some of these resistance coils are cut out of circuit; the strength of the field is thereby increased, and the potential difference can thus be kept up to the standard. The desired result can also be obtained by increasing the speed of rotation, and this method is sometimes adopted. Large machines can now be constructed with such a low armature resistance that they are sufficiently self-regulating over a considerable range; it will be explained later on that one method of obtaining a very low armature resistance is by connecting the armature conductors so that they are divided into four or even more sets placed in parallel between the brushes, instead of only two sets; and the results are so satisfactory that it would not be possible to experimentally obtain a complete characteristic curve, such as that shown in fig. 203, from one of these modern shunt-wound dynamos. The curve would remain approximately horizontal for a considerable distance from the point P, falling very gradually; and the sudden bend downwards would not be reached until the current had become too strong for the armature conductors to carry it with safety.

Although these characteristics give us a clear idea of the manner in which the external potential varies with a variation in

the current strength, we can better understand the method of combining—or, technically speaking, 'compounding'—the series and shunt windings to obtain self-regulation, by constructing and comparing other curves, which show how the external potential difference and the external resistance vary together, both in a series and in a shunt machine. As before, the ordinates (fig. 204) represent volts, but the abscissæ now represent ohms. The figure shows two curves, one for a shunt and the other for a series machine, both starting at or near the line O Y, when the external resistance is very low. In the case of the shunt machine, the

FIG. 204



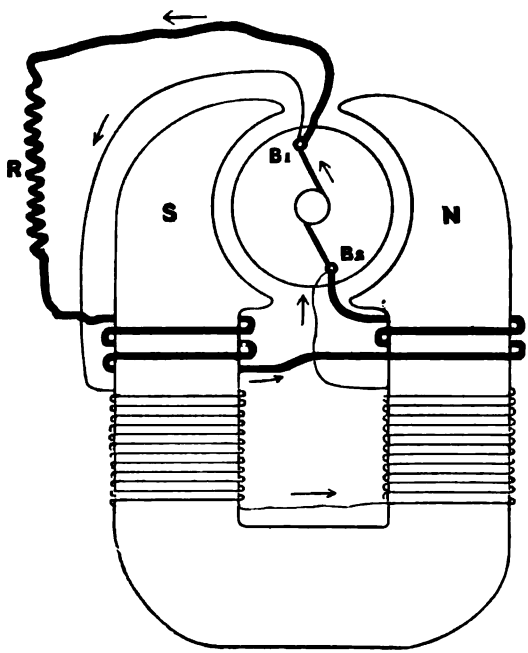
curve shows the potential difference to be very low at first, gradually rising for a short distance as the external resistance is increased, until at a certain stage it ascends suddenly, this, as we know, occurring when the external resistance is high enough to allow the field-magnets to become strongly magnetised. On the other hand, the curve from the series machine is at its highest point B when the resistance is low, and it falls almost in the same manner as the other curve rises. The series curve can hardly start on the line O Y, because, of course, when the resistance between the terminals is *nil* no difference of potential can exist at the

brushes, but it quickly reaches the highest point as the resistance is increased, and then rapidly falls as the further increase of resistance reduces the current sufficiently to considerably weaken the field. Now, if in one machine it is possible so to proportion the shunt and series windings that the maximum effect of the series coil is about equal to the maximum effect of the shunt coil, and also that the effect of the series coil diminishes in the same proportion as the effect of the shunt coil increases, these two windings will counterbalance each other through a considerable variation of external resistance, and the result will be a constant external potential difference. The first condition would make the height of the highest points on each curve equal; while if the second condition were attained, the slope downward of the one curve would exactly correspond to the slope upward of the other. And at any point such as E, the potential difference due to the series coil added to that due to the shunt coil—that is, E F + E G—should give us the vertical line E H equal to the height of the highest point on each curve. Likewise, the point of intersection A should be midway between B D and O X, and the heights of the two curves added together throughout should produce the straight line B D. Then the potential difference at the terminals being constant, the current will vary regularly with the resistance, and we shall consequently obtain a straight line for the characteristic curve of the compound-wound machine. It is evident that if the series coil acts too powerfully the effect will be to raise the point B—that is, to make the potential difference at the brushes higher when the external resistance is low and the current strong, than when the external resistance is higher, and *vice versa*.

Since, however, the effect of an alteration of the speed of rotation of the armature is so different in the case of a series as compared with a shunt machine, a dynamo compounded in the manner just described is only self-regulating at approximately the speed for which it was designed; for at any other speed the two windings do not compensate each other. If, for instance, in the case of a series machine, the speed were doubled and the external resistance increased sufficiently to keep the current the same, the strength of field would remain unaltered and the E.M.F. would be increased twofold by the double speed. On

the other hand, if, with a shunt dynamo, by increasing the external resistance we maintain the external current constant when the speed is doubled, the current in the shunt coil, and therefore the strength of the field, increases instead of remaining the same, as does that of a series dynamo. While, if at the doubled speed the resistance were reduced to make the current in the shunt coil the same as at the lower speed, the external current

FIG. 205

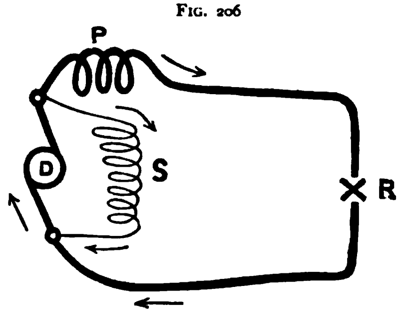


would be greatly increased in strength. Therefore, because of these different effects of an alteration of speed on the series and shunt windings, the dynamo can only regulate perfectly when driven at or near the particular speed for which it was compounded. In practice the speed at which the machine is to run is usually determined beforehand; then at this speed the shunt coils alone must be able to provide a sufficiently strong field to develop

at the terminals the required potential difference when the external circuit is disconnected, while when the external resistance is made as low as it ever will be in actual working, the ampere-turns in series should, with the assistance of the shunt coil, be able to maintain this same field.

The connections of a compound-wound dynamo, and the paths taken by the current through its coils, are typically illustrated in fig. 205. As in previous similar figures, B_1 B_2 are the brushes. At B_1 the current generated in the armature divides, part going through the shunt coils wound on the lower parts of the limbs of the field-magnet and thence returning to the brush B_2; the remainder passes through the external circuit R, then round the series coils on the upper part of the field-magnet, and thence to the brush B_2. The shunt coils are wound with comparatively fine wire, but, of course, the resistance of the series coils must be kept very low as they carry the main current, and they are composed, therefore, of a few turns of very thick wire. The relative positions of the two sets of coils is not always that shown, the series coil being sometimes wound outside and sometimes inside the shunt coil; but this not very important point is decided by convenience in construction rather than by theory. To render the path of the current even more easily understood, fig. 206 is added; R is the external circuit, D the armature, S the shunt coil, and P the series coil.

FIG. 206



In some cases a machine is designed to produce the result referred to above—that is, to make the potential difference at the brushes higher when the external resistance is low and the current strong, than when the external resistance is comparatively great and the current feeble. Let it be supposed, for example, that a large and varying number of lamps joined in parallel have to be supplied from a dynamo at a considerable distance away,

in which case the resistance of the main leads would be comparatively high, say one-tenth of an ohm. If the maximum current were 100 amperes, the fall of potential between the machine and the lamps would be $100 \times \cdot 1 = 10$ volts; but when only one-tenth of the lamps are in use the current would be 10 amperes, and the fall of potential in the mains only $10 \times \cdot 1 = 1$ volt. From this it is clear that if the lamps required a potential difference of 100 volts, a machine which could simply maintain a potential difference of 100 volts between its brushes would be unsuitable. But if its series coils were made to preponderate over the shunt coils in the manner indicated, and to such an extent that 110 volts were developed with a current of 100 amperes in the main circuit, the loss on the mains would be compensated for and the requisite potential difference at the lamps would be maintained. A machine so constructed is said to be 'over-compounded,' that is, instead of the resultant characteristic of the machine being a horizontal straight line as shown in fig. 183, it would be a line sloping upwards from D towards the axis of Y.

The over-compounding of a machine is also of service in compensating for the slowing down of its driving-engine or the slipping of the driving-belt if one is employed, both of which effects are usually appreciably greater as the current taken from the dynamo increases.

The combination of shunt and series coils for the field-magnet as described is the method frequently adopted to obtain a constant external potential, notwithstanding variations in the external circuit. We shall not refer to any other methods, many of which are only theoretically possible, but may briefly mention some interesting experiments of the Drs. Hopkinson which bear somewhat upon this point. They disconnected the field-magnet coils of a certain machine, and, having placed the brushes in the position for an undistorted field, connected them to the terminals of a Siemens dynamometer. Then, when the armature was driven at 1380 revolutions per minute, the current, due solely to residual magnetism, was 52 amperes; but on giving the brushes a slight forward lead, the current fell almost to zero, because the field due to the current in the armature was then opposing that maintained by the residual magnetism. But when a backward

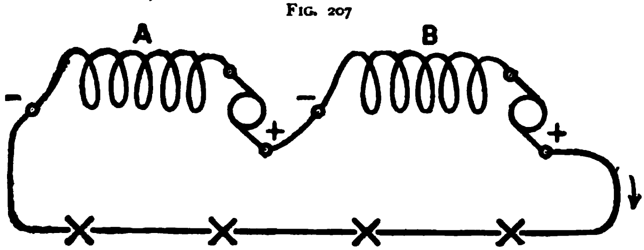
lead was given to the brushes, the polarity of the armature was shifted round so as to enhance the residual magnetism in the pole-pieces; the armature, in fact, now generated its own field, and a current of 234 amperes was obtained. Since the field in such a case is almost proportional to the current flowing in the armature, which increases as the external resistance falls, such an arrangement would regulate for constant potential; but it is not practicable owing to the destructive sparking which arises in consequence of the coils being short-circuited by the brushes while fairly active.

It should always be borne in mind, however, that the range over which a simple shunt-wound machine is self-regulating increases as the armature resistance is diminished; and as in many modern machines, more particularly large ones, such as those employed for Central Station work, the armature resistance is exceedingly low, compound winding is not resorted to so often as might otherwise be expected.

We have seen that it is possible and at times necessary to connect primary cells, sometimes in series and sometimes in parallel; the former device being adopted when an increase in electro-motive force is desired, and the latter when it is sought to obtain an increased current strength due to the reduced internal resistance. In just the same way it is sometimes necessary to join two or more dynamos, either in series or in parallel, to feed the same circuit. Connection in series is usually adopted on a constant-current circuit, such as an arc-light circuit where all the lamps are joined in series, and a current of, say, 10 amperes is required through each. Series-wound machines, of a special type to be presently described, are employed for such a purpose, and little difficulty need be experienced in throwing a second machine in circuit while the first is running, without interfering with the lamps. For example, in fig. 207, suppose the machine B to be working at nearly its full capacity, and that more lamps are wanted in circuit; it then becomes necessary to throw the second machine A in series with B to provide the required increase in electro-motive force. Now if the machine A which is at rest be joined up as shown in the figure, but with its field-magnet coils short-circuited, the whole of the current will pass

through the short-circuiting connection and through the armature, the field not becoming excited, so that the machine cannot start as a motor. The armature which is then carrying the full current of, say, 10 amperes can then be driven up to its proper speed, when the field-magnet can be thrown in circuit, so that this machine can begin to assist the other. The automatic regulators of each machine (described in Chapter XI.) should divide the work between the two, keeping the potential difference between the terminals of one machine approximately equal to that between the terminals of the other. Better regulation is, however, obtained by so arranging matters that the field-magnet coils of the two machines are joined directly in series, and the regulating shunt connected across the two, one regulator only being employed.

FIG. 207



It is clear that, if necessary, the machine B could be removed from the circuit in the same manner, by first short-circuiting its field-magnet coils, and then letting it run down, and indeed this arrangement is usually adopted when, for example, a machine shows signs of distress after a long run and requires overhauling. The second machine is first inserted in circuit, and automatically takes an increasing proportion of the work as the first one is slowed down and finally short-circuited. Appropriate switching arrangements are, of course, essential for making these changes, as the electro-motive force usually amounts to one or two thousand volts.

It is needless to mention that if the second dynamo were incorrectly joined in circuit, its field-magnet would be magnetised in the reverse direction, and the armature would, when rotated,

generate an electro-motive force opposing that of the machine already in circuit.

When lamps are joined in parallel circuit between two mains, an increase in the number placed in circuit means a reduction in the resistance between the mains, and a corresponding increase in the strength of the current which the dynamo is called upon to supply, it being imperative that the potential difference between the mains shall remain unaltered, notwithstanding considerable changes in the current strength. In such a case any dynamo employed to assist one already at work must be joined in parallel with it, and simple shunt machines lend themselves most readily to such an arrangement. A shunt machine while at rest cannot, however, be switched on to the circuit in parallel with a machine already working and maintaining a pressure of, say, 100 volts between the mains, because of the enormous current which would flow through the stationary armature. There are two paths open for such a current between the terminals of a shunt-wound machine, one through the field-magnet coils and the other through the armature. The armature resistance should be extremely low; if it were one-hundredth of an ohm the current through it would be no less than $\frac{100}{\cdot 01} = 10{,}000$ amperes, supposing the armature to remain at rest and the pressure of 100 volts to be maintained. Such a current would, if maintained, even for a comparatively brief period, burn up the armature, and although, for reasons which will be subsequently explained, it would probably not continue for any length of time, it is clear that the risk of its even starting must be avoided. Consequently, it is necessary to drive the second machine up to its normal speed, and wait until its field-magnets are fully excited and the pressure of 100 volts is developed between its terminals before switching it into circuit. An even better plan is to arrange the connections in such a way that the field-magnet coils may be joined to the main or 'omnibus' leads independently of the armature.

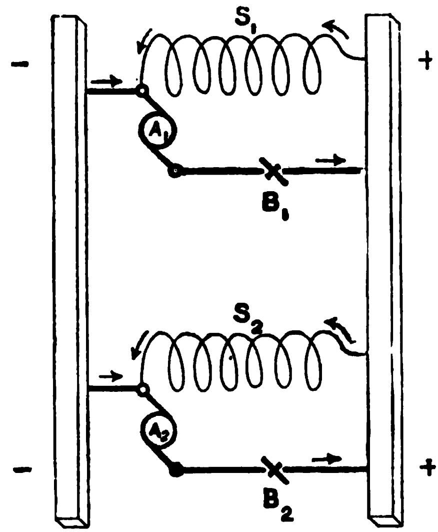
Then, in order to bring a second machine into play, its field-magnet coils are first joined across the mains, when the potential difference of 100 volts starts and maintains through the coils the requisite current to fully excite the field-magnets. The arma-

ture should then be driven up to its normal speed, and when, as shown by a voltmeter connected across the brushes, it is developing 100 volts, it can be switched in circuit, and the admission of steam to the engine cylinder increased, either automatically or by hand, until the machine supplies its share of current to the main circuit. In fig. 208 two dynamos are shown supplying a common pair of mains or omnibus bars, and of course any number of machines may be so connected. It will be noticed that in each case one brush and one end of the field-magnet coils are joined to the negative main by a common lead, in which a switch may be inserted, while another switch may be placed between the other brush and the positive main. A third switch may be inserted between the positive main and the field-magnet coils. In throwing a machine out of circuit the admission of steam should be reduced until the current passing from the armature falls to a small amount, when the armature switch can be opened without any appreciable spark passing. The field-magnet coil should then be disconnected, but if this were done without any precaution being adopted to prevent it, a considerable spark would occur at the switch contact-point, on account of the high self-induction of the field-magnet. It is therefore advisable to first shunt the field-magnet coils by a non-inductive resistance of approximately the same value, and then, when the circuit with the positive main is broken, the extra current will circulate in this shunt and die away, thus preventing any appreciable spark at the contacts of the switch.

In one of the large public supply stations a number of shunt-wound machines are worked in parallel, and an automatic switch is placed between each armature and one of the mains, as shown at B in fig. 208. This switch consists of a lever carrying a soft-iron armature or keeper, and an inverted U-shaped copper connecting piece, both on the same side of the point at which the lever is pivoted. When this end of the lever is depressed the legs of the ∩ dip into mercury cups and thus complete the armature circuit, which passes once round two soft-iron cores placed under the soft-iron keeper. When the machine is being started this connection is made by hand, and directly the current starts the soft-iron cores attract the soft-iron keeper and hold

this end of the lever down, thus maintaining the circuit. Should the current fall below, say, 25 amperes, a weight at the other end of the lever operates and immediately breaks the circuit, so that not only is the armature automatically disconnected at the right moment when the engine is slowed down for the purpose of throwing a particular machine out of circuit, but a like disconnection also occurs should any accident happen to either the engine or the machine.

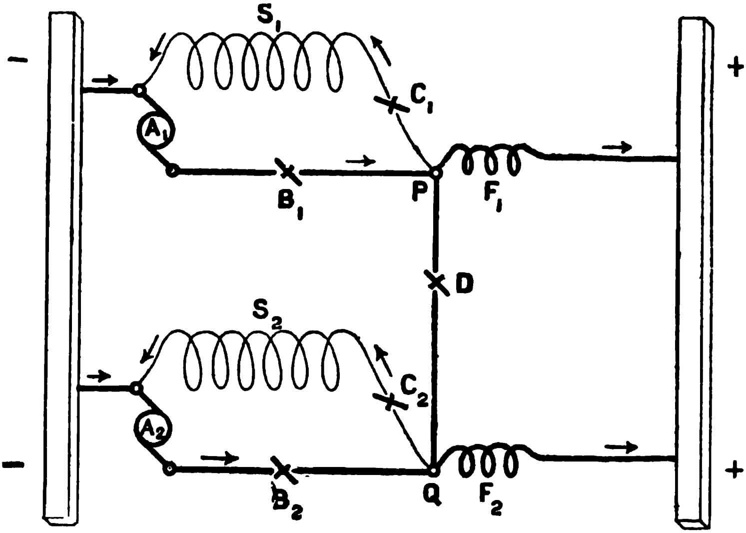
FIG. 208



Compound machines are also sometimes worked in parallel, but the arrangement is necessarily more complicated, and the liability to accident when making changes greater, than in the case of shunt machines. The method of connecting devised by Mr. W. M. Mordey and illustrated in fig. 209 is probably the best, and is certainly satisfactory when the machines are similar. Two machines are shown in the figure, connected across the positive and negative main leads, from which the lamp circuits may be tapped off, the object being, of course, to enable the load to be equally divided between the machines. One end of each of

the series coils F_1 F_2 is shown connected to the positive main, the other ends being directly joined together by the wire P Q. One end of the shunt coil S_1 is also connected to P, and the corresponding end of the shunt coil S_2 to Q, the other ends being joined to the negative main. The points P and Q are always at the same potential, or if not an equalising current will at once flow between them, and the consequence is that the difference of potential between the ends of the two series coils is always prac-

FIG. 209



tically the same, and the currents passing through them must be equal if their resistances are equal; and also the potential difference between the ends of the two shunt coils is the same and the currents in them will be equal if their resistances are equal. Therefore the strength of field will be the same for both machines, and they will equally share the work when driven at the same speed.

Should the machines be unequal the matter is not quite so simple, as among other things the resistances of the shunt and

series coils of the two machines must be so proportioned that each will get the requisite amount of current to excite the field-magnets up to their proper value.

It is evident that as the object of the wire P Q is to keep the two points P and Q at the same potential, it must be of sufficiently low resistance to prevent any appreciable fall of potential along it, notwithstanding the flow of an equalising current of considerable strength.

B_1, B_2, C_1, C_2, and D represent switches to facilitate the throwing in and out of circuit of either machine. Suppose A_2 is required to be brought into play while A_1 is working; D and then C_2 should be closed so that currents flow in the proper direction through S_2 and F_2 to excite the field-magnet coils, and then, the armature being run up to the required speed, its switch B_2 may be closed, and the machine then takes up its proportion of the work.

CHAPTER X

DIRECT-CURRENT DYNAMOS—*continued*

WE will now illustrate and describe a few typical direct-current dynamos, directing attention in each case to those details which are likely to prove most instructive in showing how theoretical principles are applied, and how, in practice, mechanical and economical considerations sometimes cause a deviation from forms which a narrow theory might show to be the best.

The student is recommended to pay particular attention to the methods adopted for securing mechanical strength and durability. It may be observed, for example, that it is quite as important to prevent the conductor being stripped from an armature as to efficiently insulate it. Again, while a waste of power, such as is evidenced by the heating of the iron core by eddy currents, is to be deprecated, any waste which shows itself in such a manner as the undue heating of bearings is equally, or even more, to be avoided. In both cases the power applied to the shaft is wasted—in the former case after, and in the latter case before, it has been transformed into electrical power.

Fig. 210 illustrates a dynamo with an armature of the Gramme ring type, the field being produced by an inverted horseshoe electro-magnet, and, although this type is not now manufactured in large numbers, there are a great many still in operation. This particular machine is compound-wound, and the arrangement is therefore similar to that depicted in fig. 205. A vertical section of the machine at right angles to the shaft is given in fig. 211. The bed-plate is of cast iron and includes a solid piece, D, in the centre, directly under the armature and field-magnet, to form the yoke of the latter. But wrought iron is employed for that portion of the cores round which the field-magnet coils are wound, each

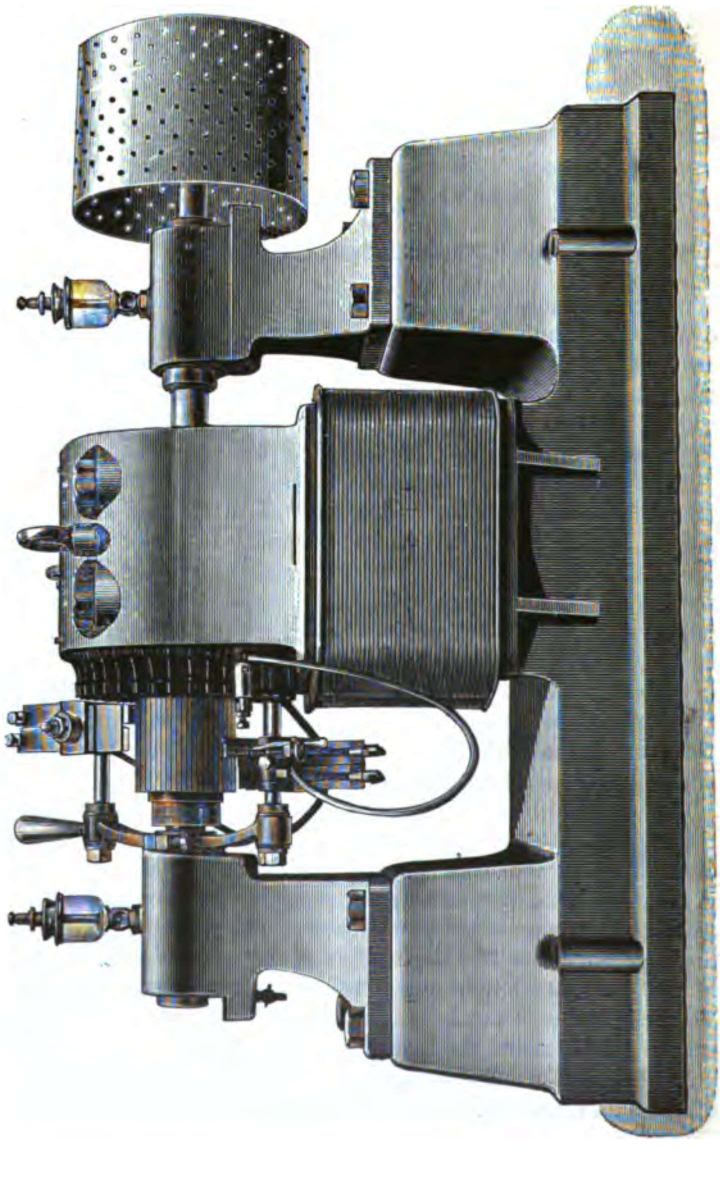
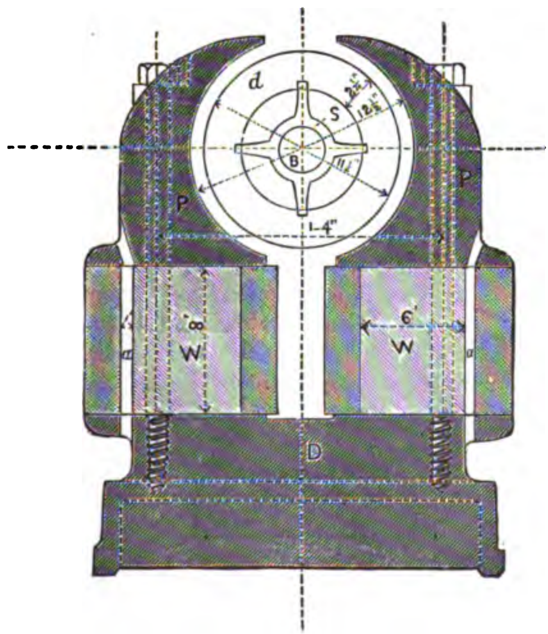


FIG. 210

core, W W, consisting of a slab of soft hammered scrap-iron; thus giving the advantage, previously referred to, of economising copper wire by obtaining the requisite magnetic conductivity with the minimum sectional area. The pole-pieces, P P, are of grey cast iron, and the sectional area of all the cast-iron portions is made greater than that of the wrought-iron portions to compensate for the lower permeability as compared with that of the excellent iron forming

FIG. 211



the core. The cast-iron pole-pieces are here tapered away to the top, the idea being that the number of lines of force to be transmitted is less in the upper than in the lower portion, but this is not good practice, as any considerable reduction of the area of the magnetic circuit in this manner tends to make the field through the armature stronger at the lower part than at the upper, with the result that there may be, especially in large machines,

a considerable downward pull on the armature. In later machines of this type the section of the iron is reduced only slightly, if at all.

Two long bolts pass through each of the pole-pieces and the wrought-iron cores, screwing, at their lower extremities, into the solid portion of the bed-plate which forms the yoke-piece, and thus holding these parts firmly together. The coils are wound so as to leave a space between the wire and the outer face of the wrought-iron core, as shown at *a a* in the figure, forming thereby a means of ventilation; for as the wire gets warm its heat is imparted to the air inside this space, and this air rising, a constant circulation is maintained and the heat carried off by a steady draught of cold air.

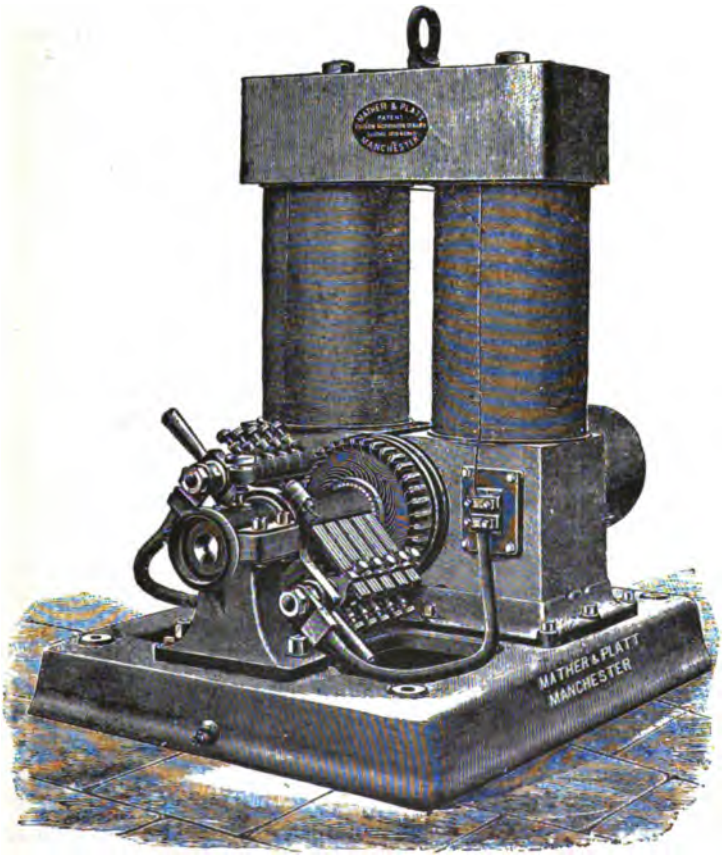
In the particular machine illustrated the thick or series coil of the electro-magnet consists of twenty-five convolutions of copper strand, composed of nineteen No. 15 wires (standard wire gauge), a stranded conductor being much more flexible and more convenient to wind than a massive solid one, although it occupies a little more space. Over this is wound the shunt coil, which consists of 2712 turns, its resistance being 20·6 ohms. In order to afford a convenient means of obtaining this resistance with this particular number of convolutions, two sizes of wire are employed —viz. Nos. 15 and 16, S.W.G.—the respective lengths of these two wires being adjusted to satisfy the conditions. The armature of this machine is constructed similarly to that illustrated in fig. 189.

The speed of the machine is 1050 revolutions per minute, at which it is capable of giving a current of 75 amperes, with a potential difference at its terminals of 100 volts.

The brushes are fixed in adjustable holders, which are carried by the horizontal arms projecting from the rocking lever, as shown in fig. 210. This lever is provided with an insulating handle, by means of which it can be rotated in either direction round the axis of the shaft, thus affording facilities for altering the lead of the brushes to suit the requirements. Each brush can also be fed through its holder while the machine is running by means of a 'feed' screw. The lever is carried on a projection from the standard supporting the bearing, and is made in two pieces bolted together, so that it can be readily tightened up on its bearing, or,

if necessary, removed. The horizontal arms are insulated from the lever by hard fibre collars; and, in addition to the feeding screws, spiral springs, with adjusting screws, are provided for

FIG. 212



varying the pressure of the brushes on the commutator, the pressure being always as light as is consistent with reliable contact.

In fig. 212 is illustrated the Edison-Hopkinson dynamo, which differs from the machine just described in that the armature is

placed at the lower ends of the field-magnet cores; an arrangement which has the disadvantage that the iron bed-plate more or less magnetically short-circuits the pole-pieces, and affords a path through which some of the lines of force leak, instead of passing through the armature. On the other hand, there is the advantage that the centre of gravity of the moving parts is kept low, thus adding to the stability of the machine; and also in some cases affording facilities for driving direct from a steam-engine fixed upon the same bed-plate. The type of machine is one which is not now used to any great extent, but it is allowed to retain its position in this chapter because of the important lessons which may be derived from a study of its details. The leakage above referred to is reduced by interposing a massive slab of zinc between the pole-pieces and bed-plate. We will endeavour presently to see to what extent this is successful.

Each of the circular field-magnet cores, together with its pole-piece, is a single forging of wrought iron; the yoke is also of wrought iron, rectangular in shape and very massive; it is secured to the cores by two bolts, the surfaces in contact being made to fit truly, so as to avoid, as far as possible, the introduction of any magnetic resistance. The armature-shaft bearings are of phosphor-bronze, and are carried by short cast-iron standards bolted on to the bed-plate. The armature is drum-wound, and its core is built up of thin discs, insulated with paper, and threaded on to the Bessemer steel shaft. Two thick, stiff end-plates hold the core discs in position, one bearing against a washer which is shrunk on to the shaft, while the other is driven up tight by a large nut. There are forty sections in the armature of the machine illustrated, each of one convolution, and the conductor consists of thick copper bars insulated with prepared rubber tape, the cross-connections being made with stiff copper strips. These strips, the outer set of which can be seen in the figure, are led round spirally to the segments of the 40-bar commutator in such a manner that a coil whose plane is vertical is connected to segments which lie near the horizontal, and, consequently, the diameter on which the brushes are set is nearly parallel with, instead of at right angles to, the direction of the lines of force through the armature.

The machine is shunt-wound, the wire composing the field-magnet coils being rectangular in section, thus reducing the waste space between the adjacent convolutions. The terminals of the machine are fixed to boards mounted on the pole-cheeks, and the marked difference in the size of the massive conductor which carries the whole current from the brush-bar to the terminal, compared with the thinner shunt-wire which passes up the sides of the field-magnet coils, will be observed. When driven at 475 revolutions per minute, this machine, which weighs about $4\frac{1}{2}$ tons, is capable of developing 52,500 watts (105 volts, 500 amperes), and on account of the low resistance of the armature it is practically self-regulating through a considerable range. Each brush-holder carries five copper wire-gauze brushes, all adjustable independently, and by this means a sufficiently large bearing surface upon the commutator is obtained without introducing any difficulty in compensating for unequal wear, such as would arise if one undivided brush were employed.

Some shunt-wound machines of this type, built for Central Station work, on the 'three wire' system were constructed to develop a potential difference of 410 volts. In each case the armature conductors consisted of stranded copper bars, the armature resistance being 0·0117 ohm. The resistance of the shunt coils was 52·7 ohms, so that the current through these coils was $\frac{410}{52 \cdot 7} = 7 \cdot 78$ amperes. At a speed of 400 revolutions per minute the current developed was 590 amperes, representing an output of about 242 kilowatts. The weight of the armature was 2 tons 19 cwt., and of the whole machine 24 tons 8 cwt. When tested, the electrical efficiency at full load was found to be 97·2 per cent., and the commercial efficiency 95 per cent.

This dynamo is interesting from the fact that it has been carefully studied and tested by the Drs. Hopkinson, the results having been published in various papers. The object of the tests was (*a*) to endeavour to gain such information as would enable the performance of a dynamo to be predicted, when its configuration and the various dimensions and qualities of the material employed (especially the iron) are known; and therefore (*b*) to enable any machine desired to give certain results at a

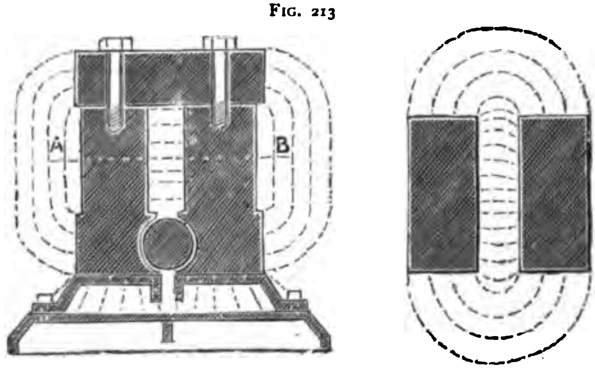
certain speed to be designed with a greater degree of accuracy than had previously been obtained.

We know that in every machine more lines of force are generated than actually pass through the armature core, the difference being caused by leakage at various points.

We will briefly describe one portion of the experiments, with the view of enabling the student to better judge of the amount and locality of such leakage in any given machine.

The portion of the experiments referred to consisted, in the first place, of determining exactly the ratio of the lines of force generated in the field-magnet to the lines passing through the

FIG. 213



armature core. This ratio will, of course, always be greater than unity, and may be denoted by v.

In fig. 213 a machine with rectangular cores is shown in section, and lines of force are sketched to roughly indicate the principal paths of the leakage. Some of the lines pass directly from one limb to the other, others leak out between the yoke and the pole-pieces, while many pass down through the arched slabs of zinc (on which the pole-pieces rest) into the iron bed-plate.

We have previously mentioned that it is possible to compare the number of lines of force cutting or cut by a coil of wire in two or more given fields, by placing a galvanometer in circuit with the coil and observing the deflections. As the resulting

E.M.F. is usually comparatively low the galvanometer must be a delicate one, and it is usual to employ one in which a short strongly magnetised needle is suspended by a silk fibre inside a coil of many turns, the deflections of the needle being made evident by the movement of a beam of light reflected on to a scale by a small mirror fixed to the magnet. But in such a test it is necessary that the needle shall not begin to move or change its position until the whole of the brief current has actually passed through the coil, and it is preferable to make the needle short and somewhat heavy, avoiding as far as possible the introduction of any damping effect. The number of divisions on the scale travelled over by the beam of light may then be taken as proportional to the E.M.F. developed, and therefore to the number of lines of force cut. An instrument of this type is known as a Ballistic galvanometer.

In the experiments under notice a current of 5·6 amperes was maintained through the field-magnet coils, from a battery, the armature circuit being disconnected. A single convolution of wire was then wound round the middle of one limb as at B, the ends of this wire being joined to an instrument such as that just referred to. The needle being at rest, the field-magnet coils were short-circuited, thus suddenly stopping the current in them, and the lines of force, in collapsing, cut the single turn of wire and induced a current therein, which, passing through the galvanometer, deflected the beam of light for a moment. The needle having again settled itself steadily at zero, the short-circuiting connection was removed, thus once more suddenly passing the current through the magnet coils. The lines of force in springing outwards again cut the single coil, inducing a current which deflected the needle to an almost equal extent, but in the opposite direction to that produced by the first current. In this case the mean of the two deflections was 264 divisions, which, neglecting the small amount of residual magnetism, may be taken as proportional to the induction in, or the number of lines of force passing through, the field-magnet limbs. The next step was to determine what proportion of these lines passed through the armature, which was of the drum type, each coil consisting of one convolution only.

The wires leading from the galvanometer were soldered one to each of two adjacent commutator bars, and the armature placed so that the plane of the coil connected to those bars lay at right angles to the lines of force.

The field-magnets were excited as before by a current of 5·6 amperes, and the deflection noticed, first when the current in them was stopped by short-circuiting, and again when the current was sent round them a second time; so as to suddenly withdraw lines of force from, and then to thrust them through, the armature core. The mean of these two deflections was 200 divisions, and therefore

$$\frac{\text{Induction through field-magnets}}{\text{Induction through armature}} = \frac{264}{200} = 1{\cdot}32 = v.$$

That is to say, 24·24 per cent. of the total number of lines of force generated failed to reach the armature core owing to leakage. Although this method does not give us the actual number of lines of force in C.G.S. units, it nevertheless gives the proportion correctly, and in these experiments the actual number passing through the armature was estimated in C.G.S. units by running the machine at a known speed and measuring the resulting potential difference, without allowing a current to pass through the armature and distort the field. We have already given the formula

$$\text{E} = \frac{\text{N P} n}{10^8} \text{ volts,}$$

where N is the total number of lines of force passing through the armature, P the number of active conductors round the armature, and n the number of revolutions per second, and consequently in the experiment under consideration $\text{N} = \frac{10^8 \times \text{E}}{\text{P} \times n}$, where E is observed potential difference in volts. Then the actual number of lines in any other part of the magnetic circuit could be found by simple proportion. Having shown that 24·24 per cent. of the lines of force were lost by leakage, the next step was to localise that leakage—that is, to discover at what points it occurred. This time the galvanometer, being less sensitively adjusted, gave a mean deflection of 115

divisions with one turn round the middle of one limb, when a current of 5·6 amperes through the field-magnets was suddenly stopped and started as before. Four convolutions were next wound round the bed-plate directly under the armature shaft, and, the current being stopped and started in the field-magnets, the galvanometer indicated a mean deflection of 50·25 divisions, due to the lines of force which leaked through the bed-plate and cut the four convolutions wound round it. Four turns were employed in order to get a fairly high deflection. The induced E.M.F. being, however, four times that which would be obtained with one turn, it becomes necessary, to enable this result to be compared with the previous one, to reduce it to the value of one convolution, thus:

$$\frac{50{\cdot}25}{4} = 12{\cdot}6 \text{ divisions, nearly.}$$

The leakage through the space between the field-magnet limbs was measured with a coil of ten turns wound on a square frame, and by a similar calculation was found to be proportional to eight divisions with one convolution.

The horns of the opposite pole-pieces approach each other both above and below the armature to within 12·7 centimetres, the depth of each being 8 centimetres. The leakage across each of these gaps was found to give 1·6 divisions, or 3·2 divisions for the two.

Reducing these losses to percentages of the total induction, we have

The leakage through the zinc plate and iron base	= 10·3	per cent.
The gaps between the horns account for	2·8	"
And the area between the limbs . .	7·0	"
Making a total loss accounted for . .	20·1	"
Out of an observed loss of . . .	24·24	"

The leakage through the shaft, and from pole-piece to yoke, and from one pole-piece to the other by exterior lines, will account for the remaining 4·14 per cent.

The ratio, v, will of course vary slightly with different exciting currents in the field-magnet coils, especially when the iron

approaches the saturation-point, because the permeability of the iron decreasing with the induction through it, while that of the air remains constant, the proportion of leakage will be greater. It is easy to give the current passing through the field-magnet coils such a value that the cores and yoke will be magnetised to the same extent as when the machine is fully loaded, but to make the result accurate the armature should also be running and carrying its maximum current. Under these circumstances the leakage would undoubtedly be somewhat greater, as the permeability of the armature core would be reduced, and the demagnetising effect due to the heavy armature current would also tend to increase the leakage.

These experiments constituted the first definite attempt to discover the extent and the locality of the leakage of lines of force generated by the current in the field-magnet coils, and it will be seen that about a quarter of the field generated in this particular case was wasted.

It should be remembered, however, that as the whole of the power expended in maintaining the field represents but a small fraction of the total power developed by a well-designed machine, this comparatively large percentage of waste field does not reduce the total efficiency to such an extent as might be at first sight supposed. The ratio $v = 1{\cdot}32$ found for this particular machine may be taken as approximately the value for most machines of this type, as the low magnetic resistance of the drum armature and the massive cores and pole-pieces bring the leakage to a fairly low value in spite of the proximity of the bed-plate. For machines of the radial pole type such as that shown in fig. 225, v is, on the average, about $1{\cdot}15$.

The value of the co-efficient of leakage v being approximately the same for all machines of similar pattern, it is usually determined for one machine only and employed in designing other machines of different sizes, and the following considerations will serve to show the manner in which it may be so employed.

Suppose in the case of a machine such as that shown in fig. 212 it be desired to calculate the number of convolutions of, and the strength of the current which must be maintained through, the field-magnet coils (that is to say, to calculate the ampere turns) in

order to project a certain number of lines of force N through the armature. We have already seen that for any simple magnetic circuit

$$N = \frac{M}{R}$$

where N represents the total number of lines of force, M the magneto-motive force $\left(\frac{4\pi}{10}\right.$ or 1·2566 times the ampere turns), and R the magnetic resistance of the circuit. Consequently

$$M = N \times R ;$$

that is to say, the requisite magneto-motive force may be found by multiplying together the total number of lines of force required to be produced and the magnetic resistance. In the case of the dynamo under consideration, the magnetic circuit is made up of three distinct sections (see p. 257), viz. the armature core, the two air-gaps, and the field-magnet core, with its pole-pieces and yoke —and in order to obtain N lines through the armature, v N (in this instance 1·32 × N) lines must be urged through the field-magnet cores. If R_1 R_2 R_3 represent respectively the magnetic resistances of the armature core, the two air-gaps, and the field-magnet cores and yoke, then the value of the requisite magneto-motive force

$$M = N R_1 + N R_2 + v N R_3 ;$$

and as M is equal to 1·2566 times the ampere turns, the value of the ampere turns can be obtained by dividing the right-hand side of the equation by 1·2566 or by multiplying by 0·8.

Since the magnetic resistance of any magnetic circuit, or of any portion thereof, is proportional to the length and inversely proportional to the sectional area and the permeability, the values of R_1 R_2 R_3 may be stated in terms of the dimensions and permeability of the respective parts. In order to determine the permeability, the maximum number of lines per square centimetre, B, at which the armature and field-magnet cores are to be worked, must be decided upon beforehand, and then, from the magnetisation curves for the particular kinds of iron employed, the permeability of the armature core (μ_1) and of the field-magnet cores and yoke (μ_3) can be obtained.

If l_1 represent in centimetres the mean length of the path of the lines of force through the armature core, and a_1 the area of the iron in the core, taken at right angles to the direction of the lines of force, then

$$R_1 = \frac{l_1}{a_1 \mu_1}.$$

In calculating the value of a_1 due allowance must be made for space occupied by the paper or other insulating substance separating the core discs.

Similarly the magnetic resistance due to the air-gaps is

$$R_2 = \frac{2l_2}{a_2},$$

where l_2 is the distance between the surface of the armature core and one of the pole-faces, and a_2 the area of one of the pole-faces. The length l_2 is, of course, multiplied by 2 because there are two similar air-gaps, but the area a_2 does not correctly represent the area of the path of the lines of force through the air-gap to the armature, because the lines spread out somewhat as they leave the edges of the pole-faces, and enter the armature core over a rather greater area than that of the pole-face. This increase of area tends to reduce the magnetic resistance of the air-gap, and should be allowed for. It has been found that, nearly enough for all practical purposes, the increase in area may be considered as a fringe round the periphery of the pole-face, the width of this fringe being equal to four-fifths of the distance l_2 (because, of course, the tendency to spread out increases with l_2), and this increased area should be inserted in the equation as the value of a_2. The permeability of air and of the copper wire occupying the space referred to as the 'air-gaps' being unity, the permeability symbol need not enter into the expression for the magnetic resistance of the air-gaps.

The magnetic resistance of the field-magnet cores, yoke, and pole-pieces is

$$R_3 = \frac{l_3}{a_3 \mu_3},$$

where l_3 is the mean length of the path of the lines of force from one pole-face to the other, a_3 the area of cross-section, and μ_3 the permeability of the iron. In this case it is assumed that the iron of the field-magnet is uniform throughout, but as this is rarely the case, it is frequently necessary, in order to obtain accurate results, to treat separately the pole-pieces, yoke, and the limbs over which the wire is wound. The permeability and sectional area of each part can then be dealt with separately, as also the value of N, which on account of leakage is less in the pole-pieces and greater in the middle of the yoke than at any other part of the field-magnet. But assuming for the sake of simplicity that the iron of the field-magnet is uniform throughout, and that the full number of lines, viz. v N, pass through the entire length of pole-pieces, magnet cores, and yoke, it is evident that the magneto-motive force required to project N lines through the armature may be written

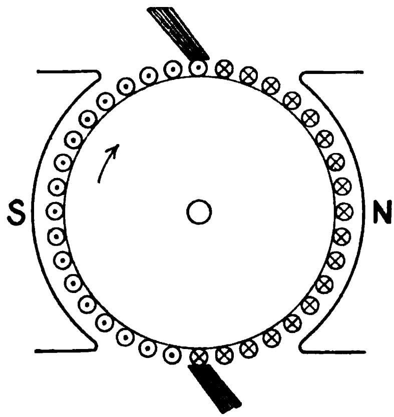
$$\text{M} = \text{N}\frac{l_1}{a_1\mu_1} + \text{N}\frac{2l_2}{a_2} + v\,\text{N}\frac{l_3}{a_3\mu_3}.$$

The magneto-motive force so found would be sufficient to urge the requisite number of lines of force through the armature in the absence of any disturbing effect due to the current in the armature itself. We know that when the brushes are set with absolutely no lead, the armature field is projected at right angles to that of the field proper, but, when the brushes are shifted forward, the current flowing in a few of the active conductors actually strives to set up lines of force in the opposite direction to those due to the field-magnets. This back magneto-motive force must be allowed for by adding to the field-magnet coils such a number of convolutions as, with the particular current flowing through them, will give a number of ampere turns equal to the ampere turns on the armature acting in opposition to the field.

A little reflection will show that the number of active conductors on the armature so acting in opposition to the field will be all those included in the arc on each side of the magnetic axis, subtended by the angle of lead taken on both sides of the zero point.

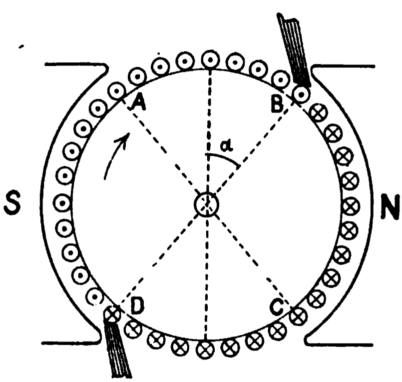
A reference to figs. 214 and 215 will perhaps make this a little clearer. In fig. 214 a diagrammatic sketch of a dynamo is shown in which the brushes are set in the geometrically neutral zone—that is to say, at points midway between the pole tips. The direction of the current flowing in the conductors is indicated by a dot when the current is supposed to flow through the plane of the paper and towards the observer, and by a cross when the current is supposed to flow away from the observer through the plane of the paper. It will be seen that in the case of fig. 214 the armature field is at right angles to the main field.

FIG. 214



In fig. 215 the brushes have been given a lead of *a* degrees, and in this case the belt of conductors A B, C D produces a field in direct opposition to the main field, and the belt B C, D A produces a field at right angles to the main field. Thus the conductors producing a demagnetising effect are those embraced by an angle equal to twice the angle of lead on each side of the axis of the main field.

FIG. 215



Suppose, for example, the lead of the brushes to be 4° and the number of active convolutions round the armature be 180,

this will give for the case of a drum armature a total of 360 active conductors. In twice the angle of lead, therefore, there will be eight active conductors on each side of the main field axis, or eight active convolutions producing a demagnetising effect on the main field. If the current flowing through the armature were 200 amperes this would give $8 \times 200 = 1600$ ampere turns setting up a back magneto-motive force. Consequently, if the current flowing through the field-magnet coils were four amperes this would mean an addition of $\frac{1600}{4} = 400$ convolutions to the winding of the coils of a shunt machine; while if the machine were compound-wound the necessary addition would be made to the series coils, because the back magneto-motive force, like the current in the series coils, increases with an increase of the load.

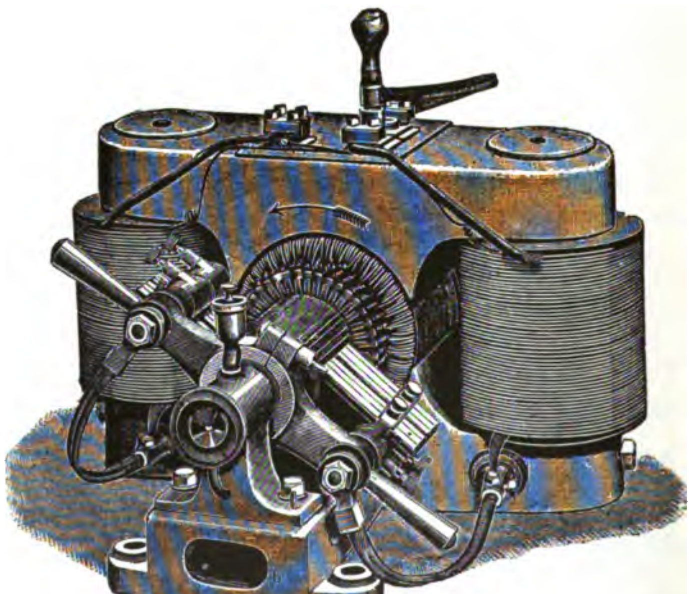
A fourth term representing this additional magneto-motive force should be added to the right-hand side of the equation given above. It will be $\frac{4\pi}{10}$ times those ampere turns on the armature which are opposing the field; and in any case in order to obtain the *ampere turns* required for the field-magnet coils, the right-hand side of the equation (which now represents the magneto-motive force) must be divided throughout by $\frac{4\pi}{10}$, which is equivalent to multiplying by 0·8.

A few other points which have to be taken into consideration in designing a dynamo are referred to in the various chapters in which machines are described.

The 'Manchester' dynamo, which is another good machine in which the Drs. Hopkinson were largely concerned, but which represents another type of machine gradually passing out of use, is illustrated in fig. 216. The arrangement of the field-magnets differs somewhat from that in the machines hitherto described. Two electro-magnets are fixed vertically with their like poles uppermost, the similar poles being in each case joined together by massive cast-iron yokes, shaped as shown, so as to form the pole-pieces between which the armature rotates. The lines of force due to the two field-magnet coils meet at the pole-pieces and pass through the armature in the manner indicated by the dotted lines

in fig. 217. The vertical members of the field-magnets are of wrought iron, let into the horizontal yokes, which, being of cast iron, have about twice the sectional area of the cores. The lower casting is extended on both sides so as to form the bed-plate of the machine, and the centre of gravity of the moving parts being low, it is comparatively easy to rigidly fix the machine so as to obtain great steadiness in running.

FIG. 216

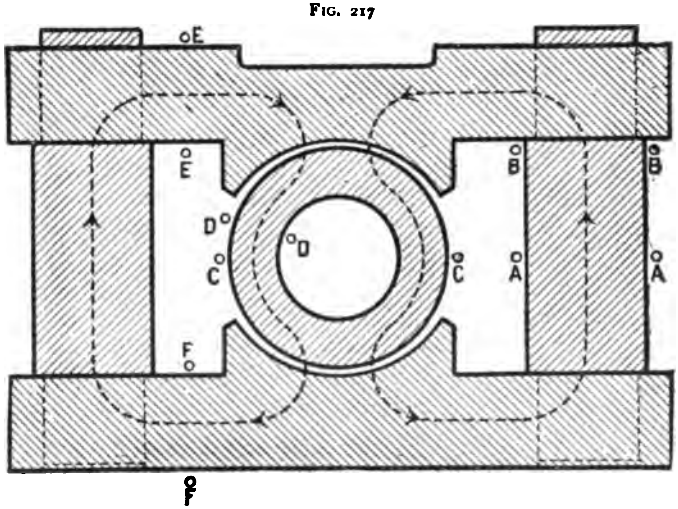


The shaft carrying the armature is made of Bessemer steel, the bearings being of gun-metal, and a free space along the shaft is provided to admit air for ventilating the armature. When driven at 1100 revolutions per minute, the machine illustrated, which is compound-wound to maintain a potential difference of 100 volts, is capable of generating a current of 80 amperes, or a maximum output at this speed of 8000 watts. All other sizes of the Manchester dynamo are similar in appearance and construction to

that shown in the figure, except that in the case of shunt-wound machines the heavy conductors for the series winding are absent.

The commutator consists of forty bars of hard-drawn copper insulated with mica. Each arm of the rocking lever carries two or more wire-gauze brushes, each brush being independently adjustable. The diameter of commutation with machines of this class, in which the direction of the lines of force through the armature is vertical, approximates to the horizontal, and this position in the Manchester machine is more nearly approached in consequence

FIG. 217



of a peculiarity in the curvature of the pole-pieces. Instead of the polar surfaces being made concentric with the armature, they are struck from a radius greater than that from the centre of the shaft, so that the pole-pieces are brought slightly nearer the armature at points opposite the extremities of its vertical diameter. The resistance of the path for the distorting flux, due to the current in the armature, is thus increased, and the distortion correspondingly diminished.

The armature is of the ring type, the core consisting of the usual thin iron discs clamped between the ends of a gun-metal

frame. The arms of this frame, which fit into slots in the discs, are free of the shaft, so that a clear space for ventilation is retained. The end-plate nearest the commutator is keyed to the shaft, while the other is held up tight against the plates by means of a nut. The wire is wound in forty pairs of coils, the resistance from brush to brush being 0·084 ohm. The shunt coils on the field-magnet have a resistance of 41·5 ohms, and the series coils, which are wound outside the shunt coils, have a resistance of 0·049 ohm. The gross weight of the machine is $10\frac{3}{4}$ cwt.

The brothers Hopkinson also made on this machine some experiments similar to those already described, and we may briefly refer to the simpler of the experiments, which show the percentage and the locality of the leakage of the lines of force. Fig. 217 gives an outline of the field-magnets and armature core, and shows the various positions of the testing-coils. As in the other experiments, the armature was disconnected, and a constant current obtained from an independent source to magnetise the field-magnets, the lines of force being made to cut the testing-coil by suddenly starting and stopping the current in the field-magnets, and the mean of the two observed deflections of the ballistic galvanometer calculated as before. In the first experiment four turns were taken round the middle of one limb at A A, and the mean deflection was observed to be 214 divisions. But as with a single turn of wire only one-fourth of this would have been obtained, $\frac{214}{4} = 53{\cdot}5$ represents the total induction through the field-magnet core in terms of the arbitrary unit here assumed. But an equal number of lines pass through the other vertical limb; therefore, the total induction through the field-magnet cores, as shown by this first measurement, may be represented by 107.

The student should here note the difference between a field-magnet wound as in the case under consideration with two coils arranged to produce 'consequent' poles, and the arrangement shown in fig. 212. In the present case the two coils may be considered as acting in parallel, as the lines of force developed by one coil should not pass through the other coil; while when the two coils are wound on the limbs of a single horsehoe-shaped magnet they may be considered as acting in series, and with the

exception of those lines lost by leakage, all the lines of force developed by one coil pass through the other.

The coil was next raised to B B, where the mean deflection was 206, or, for a single turn, $\frac{206}{4} = 51 \cdot 5$ or 103 for the two limbs, and the mean of these two results—viz. 105—was taken as representing the mean induction in the field-magnet cores.

Three turns were wound round the armature at C C, where the deflection obtained was 222 divisions, or, for one turn only, $\frac{222}{3} = 74$, which represents the total induction through the space occupied by the armature. But we know that in a Gramme ring a certain number of lines pass diametrically across instead of round the armature core, which number becomes greater when the iron is so saturated that its permeability is low—perhaps lower even than that of the shaft—and the next experiment sought to determine the waste due to this cause. Four turns were taken round D D, the deflection being 141, or 35·25 in terms of one convolution. But as an equal number of lines pass through the other half of the ring, we must double this, getting 70·5 as the effective induction through the core, against 74 through the whole armature space and 105 through the field-magnets.

At E E 39·75 divisions due to one convolution were obtained, and, the induction being the same on the other side, the total induction = 79·5.

At F F the result was higher, being 41·75, or 83·5 for both sides, the difference being caused by the easier path at the bottom of the machine offered by the bed-plate and bearings, and, of course, these additional lines are wasted.

We see, therefore, that in this case a large number of the lines of force generated are wasted; in fact, here

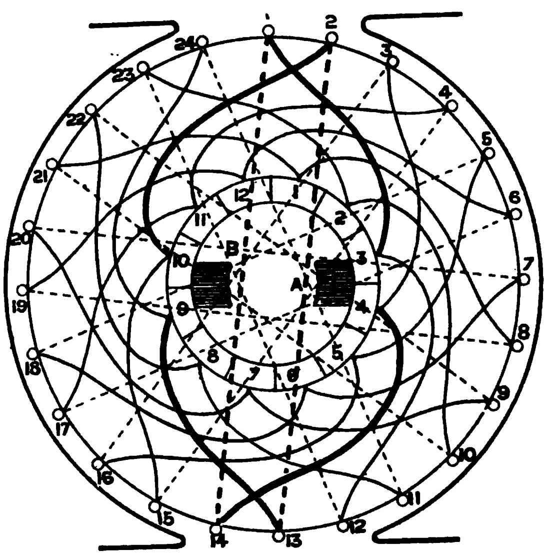
$$v = \frac{\text{lines through field-magnets}}{\text{lines through armature core}} = \frac{105}{70 \cdot 5} = 1 \cdot 49 \text{ nearly.}$$

This loss is partly accounted for by the extension of the lower yoke-piece to form the bed-plate, and the use of iron supports for the bearings, and is, no doubt, fully compensated for by advantages from a mechanical point of view. But it will be observed

that almost 5 per cent. of the lines passing through the armature leave the core and pass diametrically across the ring; this large proportion is in a great measure due to the fact that induction through the armature coils was very high, viz. 20,000 C.G.S. units.

Before proceeding to a discussion of the machines of present-day design it is, perhaps, desirable that some attention should be devoted to the method of winding the armature conductors, and we will commence by considering the case of a simple two-pole

FIG. 218



machine with a smooth armature core. In fig. 218 such a machine is shown diagrammatically, the armature having twelve coils and each coil consisting of two conductors, giving a total of twenty-four conductors or bars. The commutator has twelve segments, the number of segments thus being the same as the number of coils, as is usually the case. The connections of the bars to the commutator are shown by curved lines, and the straight dotted lines show the back end of the coils. The scheme of connections is such that one conductor is joined through a commutator

segment to the conductor *nearly* diametrically opposite. The diametrically opposite bars must not be connected, otherwise it would not be practicable to join up all the conductors and still maintain the symmetry of the arrangement. Starting from conductor 1 we connect to segment 3, thence to conductor 12, and back to conductor 23, always joining the odd-numbered bars to the even-numbered ones and *vice versâ*. All the connections are made symmetrically, and after all the bars have been joined in this way we come back to bar 1, and thus the winding is closed. The brushes are placed on the commutator in such a position that they touch the segments connected to the bars near the neutral zone. In the case shown in fig. 218 it is seen that the brush B short-circuits the coil 2–13 and the brush A the coil 1–14. It is also to be noticed that the current can reach the brushes by means of two paths. For instance, the current can take the path from brush B to segment 9, and through the bars 24, 11, 22, 9, 20, 7, 18, 5, 16, 3 back to brush A; or from brush B to segment 10 and thence to bars 15, 4, 17, 6, 19, 8, 21, 10, 23, 12, back to brush A; that is to say, the conductors are arranged into two sets of 10 in series, and the two sets are connected in parallel by the brushes, and two bars are short-circuited by each brush. This is the simplest possible case of a drum-wound armature.

It often happens that a coil, instead of being constructed by simply joining together the two conductors, as shown in the figure, consists of a number of turns of copper wire or copper strip, especially when it is desired to obtain a high voltage without increasing the number of commutator segments unduly. In such cases each side of the coil may be considered as one bar as far as the connections are concerned, and the ends of the coils joined up precisely as is indicated in fig. 218. As a matter of fact, increasing the number of turns in the coil has the same effect as increasing the length of the armature.

By far the largest number of machines are now made on the multipolar system, a system which will be described in detail presently, but which for our present purpose may be referred to as one in which the machine has four or more field-magnet poles; the armature of such a machine is usually provided with slots for the reception of the coils. The objects in using a slotted arma-

ture have been explained in the previous chapter, but may be briefly repeated here. First, it is possible by the use of slots to make the armature mechanically more perfect, since the conductors are positively driven by the core-plates and it is practically almost impossible to strip the conductors from the core. In the second place, it is easy to bring the surface of the armature core much nearer to the pole-faces, and thus by reducing the air gap to reduce the magneto-motive force required to maintain a field of the requisite strength through the armature core.

When connecting up the conductors of a slotted armature in which two or more conductors per slot are provided, it is necessary that the conductors be numbered in a definite order, and it is here assumed that there are two conductors per slot which are numbered so that the odd numbers are on the outside and the even numbers on the inside, as shown in 219 and 220.

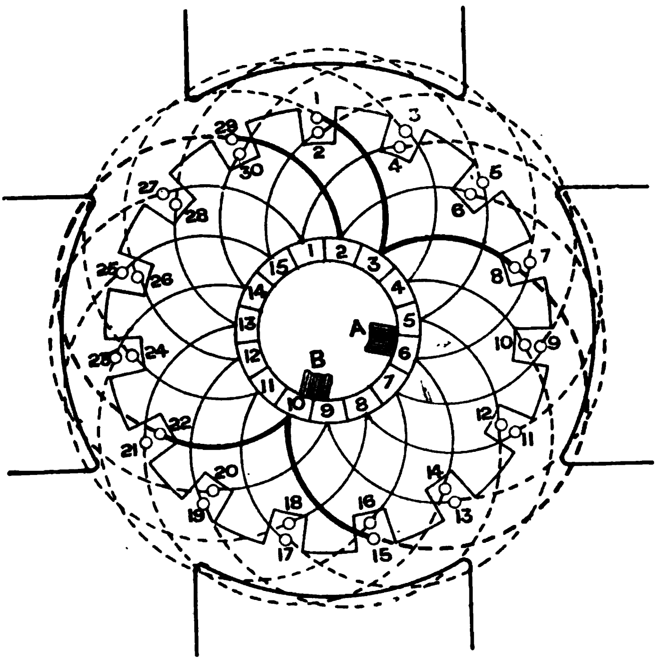
It is also necessary, in the case of multipolar machines, to distinguish between two distinct types of winding known as 'wave' or series winding, and 'lap' or parallel winding. There are one or two very important differences in these two types, the explanation of which will be more readily understood by a further reference to figs. 219 and 220. If the connections in fig. 219 are traced out it will be seen that in joining up the bars a continuously progressive round of the armature is made. Thus from bar 1 we connect to bar 8, and thence to bars 15, 22, 29, 6, and so on, thus making several complete rounds of the armature before completing the winding, and for this reason the armature is said to be 'wave wound.'

Comparing this with the scheme of winding illustrated in fig. 220, it will be noticed that in the latter case we pass from bar 1 to bar 6, and then *backwards* to bar 23, thence to bar 4 and again backwards to bar 21, and when a complete circuit of the armature has been made in this way the winding closes. This type of armature is known as 'lap wound,' the reason being clearly indicated by the overlapping appearance of the two coils shown in thick lines. This winding is also known as a parallel winding.

Returning to fig. 219, two brushes are shown displaced by 90°, and by tracing out the connections between these two brushes

we find that there are two, and only two, armature paths, and starting from one brush we do not reach the other brush until all the bars in each path have been included. Thus from brush A and segment 5 to bars 12, 19, 26, 3, 10, 17, 24, 1, 8, 15 back to brush B gives one path, and from brush A and segment 6 to bars 7, 30, 23, 16, 9, 2, 25, 18, 11, 4, 27, 20 back to brush B gives the

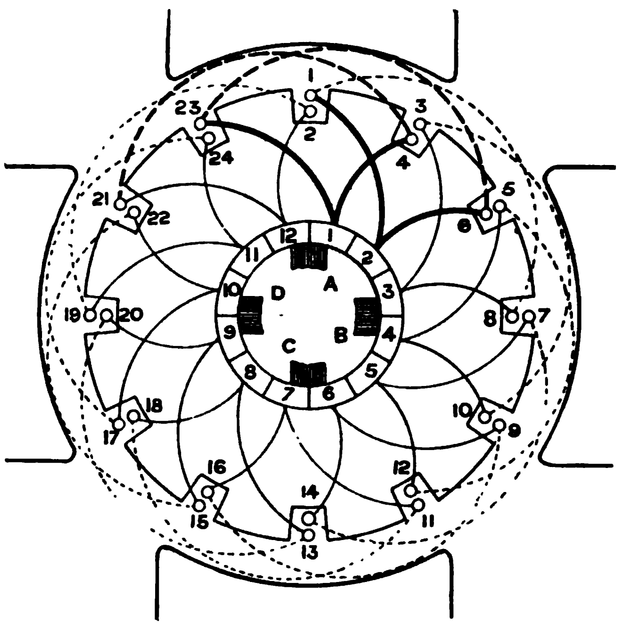
FIG. 219



other path, whilst the coils 5, 28, 21, 14, and 13, 6, 29, 22 are short-circuited by the brushes A and B respectively. It is evident that the two armature paths have not the same number of conductors in each, and this is accounted for by the fact that the number of commutator segments is odd; for this reason it is advisable to provide the commutator with an even number of commutator segments.

Following out the connections in the lap winding of fig. 220, it will be found that we pass from one brush to the next after only about one quarter of the conductors have been joined up, and it is therefore necessary, in order to usefully employ all the conductors, to provide the same number of brushes as there are poles. In such cases the alternate brushes, being of similar polarity,

FIG. 220



are connected together. It will further be found that each pair of brushes gives two armature paths, so that the total number of armature paths is the same as the number of poles. We see, then, that in a multipolar machine with a series winding it is possible to collect the current from all the conductors by means of one pair of brushes only, whilst with a lap winding it is necessary to have as many brushes as there are poles.

In calculating the E.M.F. developed in the armature of a two-pole machine we arrived (page 363) at the expression $\frac{N P n}{10^8}$. For the case of a multipolar machine it is necessary to introduce a modification of this expression for the E.M.F. in order to deduce a formula of general application to machines of any number of poles, and with either of the two types of winding mentioned above.

Taking first the case of the series winding, it is easy to see that since there are only two armature branches in parallel it follows that for one pair of poles the E.M.F. induced is $\frac{N P n}{10^8}$, while for a machine with p pair of poles the E.M.F. induced will be $\frac{N P n}{10^8} p$.

Since increasing the number of poles has the same effect as increasing the armature speed of a two-pole machine in the same ratio, the other factors in the above expression remain constant. In the case of a lap-wound machine with p poles, it will be gathered from what we have just said that the number of branches of the armature winding in parallel is equal to $2\,p$ instead of 2, as in the case of a two-pole machine. Hence since the number of conductors in series is reduced in the ratio p, and the equivalent speed is increased in the ratio p, the E.M.F. induced will be $\frac{N P n}{10^8} \frac{\times p}{\times p}$, *i.e.* $\frac{N P n}{10^8}$, or the same as for a two-pole machine.

It is, however, possible to wind an armature for a multipolar machine so that the number of paths for the current is intermediate in value between that for a pure 'series' winding and that for a pure parallel winding.

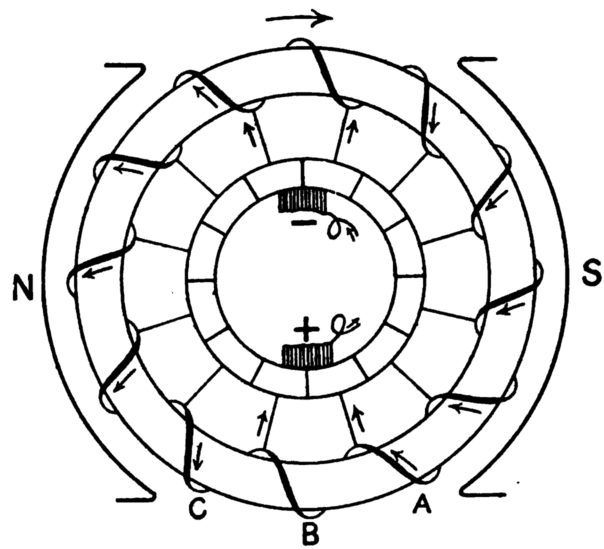
The type of winding in which this is done is known as a series-parallel winding, and was first introduced by Professor Arnold. Then, in general terms, if p be the number of pairs of poles, and a be the number of pairs of armature paths, the E.M.F. developed will be

$$\frac{N P n}{10^8} \times \frac{p}{a} \text{ volts,}$$

and this is the most general form of the expression for the E.M.F. developed.

The question of commutation now requires attention, for it must be remembered that one of the most serious difficulties which have to be overcome in designing a direct-current dynamo is that of sparking at the brushes; in fact, the output of a machine is often fixed by the appearance of sparks at the brushes,

FIG. 221

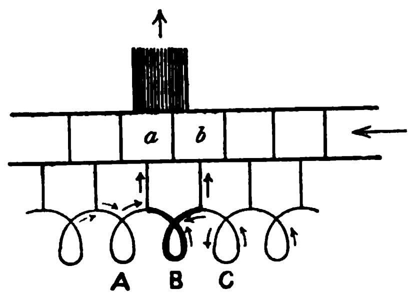


which if left unchecked may go on increasing in magnitude until they destroy the commutator.

In order to enable the student to see clearly how this phenomenon is produced, we will consider the case of an armature of the simplest type, viz.—an iron ring wound with a number of turns of copper wire, each turn being connected to a commutator segment as shown in fig. 221. The brushes are laid on the commutator, one at each extremity of a diameter, and each brush is assumed to be just a little wider than one segment. It can be shown that any winding, however complex, can be reduced to

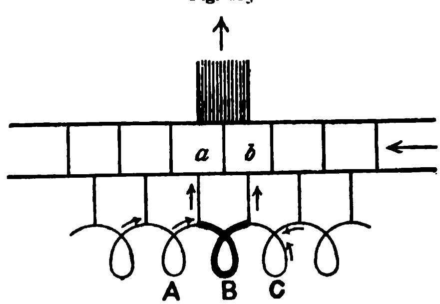
this scheme, so that what follows is of universal application. Suppose the armature to be driven in the sense shown in the figure, and that the brushes are connected to an external resistance; currents will then flow in the armature conductors in the direction indicated by the arrows. In the coil A the current flows in one direction and in the coil C in the opposite direction, whilst the coil B is short-circuited by the brush. It is thus evident that as the armature revolves each coil as it passes under the brush has the current flowing in it 'commutated,' or changed in direction.

FIG. 222



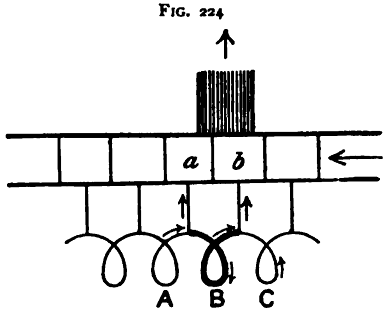
In figs. 222, 223 and 224 three stages of the commutation of the current are shown. The student will probably have learned by this time that when two conductors are placed in contact there is, and always will be, some measure of resistance at the contact surfaces. Let us assume that the whole resistance between the commutator segments and the brush resting on them is indicated by S, then when the brush rests on two segments the resistance of the surface contact of the two segments is inversely proportional to the area of contact—that is, to the width of segment covered. Thus, for example, in fig. 222 the contact resistance between the brush and the segment a is $\frac{4}{3}$ W and the resistance between the segment b and the brush is 4 W, where W represents the contact resistance of one segment. In fig. 223 the resistance between the

Fig. 223



brush and each of the segments *a* and *b* is the same, and in fig. 224 the resistance between the brush and segment *a* is 4 W and between the brush and segment *b* is $\frac{1}{4}$ W. Hence as the commutator moves forward the current in the coil B becomes gradually weaker until it falls to zero, and then gradually rises until it reaches its full value in the opposite direction. Thus by virtue of the brush contact resistance alone the current is automatically commutated. Now if this were the whole problem all would be quite simple, and as a matter of fact this is actually how commutation would take place if the machine were to run slowly enough, and if carbon brushes were used in which the contact resistance were sufficiently high. When the speed becomes appreciable, however, another factor enters into the question, and that is the self-induction of the coil in which the commutation takes place, for when the speed is sufficiently high the electro-magnetic inertia does not allow the current to change quickly enough, and unless some means be adopted to counteract this effect, sparking must be the result as a consequence of breaking the circuit in which there is an appreciable current flowing, as would be the case, for instance, if in fig. 224 the brush leaves the segment *a* while a current is still flowing in the connector between *a* and the armature coils. What is necessary, then, is that the current in the coil passing under the brush be assisted to reverse its direction, or, in other words, an E.M.F. must be induced which will help the current to take the final value it is required to have when leaving the brush. This E.M.F. will be induced by rotation of the coil in the field, which it will enter after leaving the brush, and therefore if commutation can be arranged to take place in this field we shall have achieved the desired object. This is done by giving the brushes a 'lead' in the direction of rotation of the armature, as will be clear after a moment's

FIG. 224



consideration. There are, however, limits to this method of remedying sparking, for if the lead is too much the demagnetising effect mentioned above will be excessive, and, moreover, the number of active conductors must be greatly diminished. It is now quite common to specify that a machine shall run sparklessly for all loads up to 25 per cent. overload without giving the brushes a lead, in many cases the surface contact resistance of the carbon brushes being relied on to effect the commutation.

It may be added, in passing, that all that has been said with regard to a generator applies equally well to a motor, with the important difference, however, that the E.M.F. induced by the rotation of the motor is in direct opposition to that applied at the brushes, and in order to prevent sparking the brushes have to be given a backward 'lead'—that is to say, they are moved back against the direction of rotation of the armature. The belt of conductors embraced by the double angle of lead then becomes again a demagnetising belt weakening the main field.

Within the last year or two the extended use of the turbo-generator has rendered the problem of commutation of immense importance, and the introduction of some positive means of producing a commutating field without moving the brushes out of the neutral zone has led to the use of what are known as commutation poles. These are small poles introduced between the main poles and excited by a winding in series with the main circuit, so that the armature coils undergoing commutation move in a field of a strength proportional to the armature current, and by this device the output of direct-current machines can be enormously increased for a given weight of material. The problem of commutation is, however, one of extreme complexity, and has in recent times been very carefully investigated.

It may be stated, however, as giving a general idea of the main factors entering into the question, that Professor Arnold and Dr. Mie have proved that in every case of commutation the value $\frac{S\,T}{L}$ must be greater than 1, where S is the contact resistance as above, T is the time of commutation, and L is the coefficient of self-induction of the coil undergoing commutation. In actual machines running at a given definite speed S is the only variable,

and it therefore becomes of great importance to choose the brushes of the correct quality of carbon and having a suitable contact resistance. In fact, it is often possible to cure a machine of sparking by using a more suitable quality of carbon for the brushes. Of course, in order that a machine may run satisfactorily it is essential that the commutator surface be true and even, otherwise the brushes will be set in vibration and then sparking will undoubtedly ensue, the commutator surface will become pitted, and the evil will gradually become worse until, if the fault is not attended to, a breakdown will result.

Multipolar machines with drum armatures are now very extensively employed, more especially in cases where the maximum current developed by the machine is very heavy. If a simple two-pole field-magnet be employed, considerable difficulty arises with very heavy armature currents on account of the serious reactions on the field proper, the magnitude of these reactions being approximately proportional to the number of active conductors on the armature and to the strength of the current flowing therein. Among other things, the great distortion of the field at maximum load involves a considerable lead being given to the brushes, and a comparatively slight variation in the armature current necessitates a readjustment of the brushes to prevent sparking. The difficulty can, of course, be overcome, even with a single field, but it is found to be less expensive, for machines above a certain size, to employ a field-magnet with four or more poles, the magnitude of the reactions which have to be dealt with being approximately inversely proportional to the number of field-magnet poles when the armature conditions remain constant. With multipolar machines and a parallel armature winding we can have a large number of armature paths in parallel, and thus are enabled to obtain a large current. On the other hand, multipolar machines and a wave winding are the conditions for a high voltage machine, since the voltage induced depends on the ratio of the number of poles to the number of armature paths, as is shown by the general formula given for the E.M.F.

Fig. 225 illustrates the arrangement of the field-magnets and armature of such a four-pole machine. The field-magnet coils are usually wound on the straight limbs which project inwards

from the outer framework, and each pole-face covers somewhat less than a quarter of the armature surface. The poles are alternately north and south, and the general direction of the lines of force is indicated in the diagram. It is evident that the armature conductors at opposite extremities of a diameter, which are passing under similar poles, must have induced in them a current in the same direction; for example, if the direction of rotation were right-handed, two conductors, passing respectively under S_1 and S_2, would have induced in them currents flowing upwards through the paper. If, therefore, an armature section were wound in the same way as for a two-pole machine (see fig. 218)—that is to say, if two diametrically opposite conductors formed one section of the armature and were joined to two adjacent commutator bars—no current would be obtained, the E.M.F. induced in one conductor neutralising that in the other, and this neutralisation would occur at every part of the field.

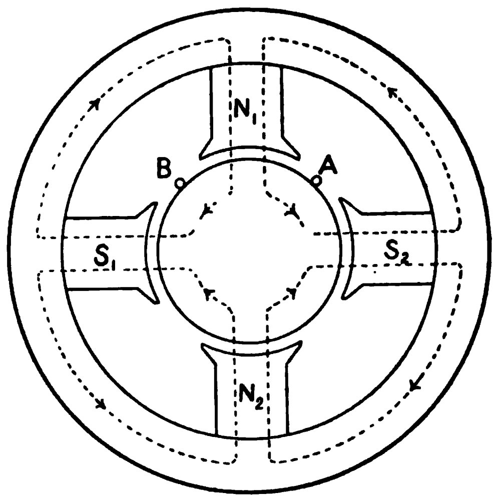
We may, in fact, select any one active conductor at any stage (except that in which commutation occurs), and we shall find that the conductor diametrically opposite it has a current induced in it in the same direction—that is to say, in any pair of diametrically opposite conductors the currents will both flow either towards or away from the commutator end of the armature. Now these pairs of conductors may be so connected that they feed the external circuit either in series or in parallel; the former arrangement is adopted when the electro-motive force is required to be comparatively high with a correspondingly low current strength, and the latter when a heavy current with correspondingly low E.M.F. is desired.

If the series connection is adopted two sets of brushes only are required, set at an angle of 90° apart, the current having two paths open to it through the armature from brush to brush, as in an ordinary drum armature. The minimum number of active conductors joined in series thus becomes four per section, the current through any one section passing, say, from front to back along the first active conductor, returning by one situated 90° further on, then passing from back to front by a conductor yet 90° further ahead, and finally returning by one still further round by 90°.

When the parallel arrangement is followed the minimum number of active conductors per section is two, situated 90° apart, and, unless a special method of cross connection is adopted, four sets of brushes are necessary, these sets being 90° apart, and the diametrically opposite pairs positive and negative respectively. In most cases, as the current to be collected is heavy, the four sets of brushes are employed, opposite sets being directly joined together externally.

In fig. 225 A and B represent two active conductors placed 90° apart, and in the case of an armature with parallel con-

FIG. 225



nections these two conductors would be joined together by a cross-connector at the back, while their ends in front would be joined to adjacent bars on the commutator. It will be seen that the coil or section of which they form the essential part embraces practically the whole of the lines of force entering or leaving any one field-magnet pole while they are in a position similar to that shown in the figure. These conductors are most active when (allowing for a slight distortion of the field) they have each just passed the middle point of their respective pole-pieces, and least

active when 90° from this point; so that the commutation takes place in this latter position, which is that indicated in the figure. In fact, it may be taken as a general rule for any type of machine that the reversal of current in, and therefore the commutation of, any one armature section always occurs at the moment when that section is embracing the maximum number of lines of force.

The student should now be in a position to study the details of typical modern machines, and appreciate the excellent manner in which established principles have been applied. A comparison of these machines with the bipolar machines illustrated in the earlier portion of this chapter will also be instructive. A modern direct-current machine with auxiliary or commutation poles, as designed by Messrs. Bruce, Peebles & Co., is illustrated in fig. 226.

The particular machine illustrated has a number of excellent features and was constructed for the Shanghai Municipal Council for a load of 650 kilowatts at a pressure of 550 volts when driven at a speed of 230 revolutions per minute, the current being about 1180 amperes. The figure gives a longitudinal section of the machine, together with an end view, half in section. A few of the principal dimensions are given in millimetres. The frame A consists of a cast-steel ring, made, for convenience of erection and repairs, in two halves, which are bolted together at B B, and this frame can be secured to the bed-plate C by means of bolts at D D. There are eight main poles, which are of rectangular section and are cast solid with the frame. The machine is of the compound type, the field-magnet coils consisting of a shunt winding and a series winding, which are coiled on separate frames or bobbins, a narrow air channel *a* being provided between the bobbins and the pole-core for the purpose of ventilation. After the coils have been impregnated and slipped into position, the pole-shoes are fixed to the ends of the cores by means of screws.

The construction of the armature is clearly shown in the figure. A cast-iron hub E, having two sets, each of eight radial arms F, is securely keyed to the steel shaft, and is cast so that it serves as a coupling by which the prime mover can be connected for driving the machine. At the other end the hub is turned

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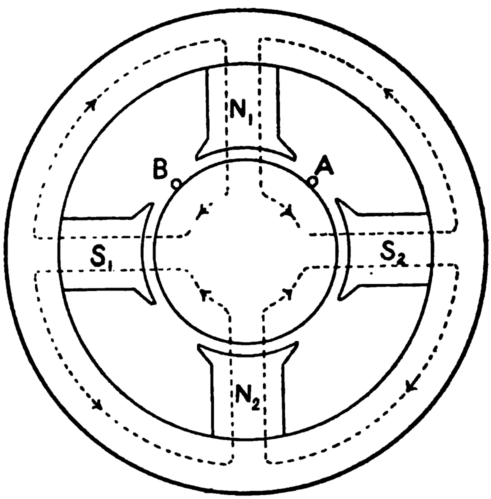
FIG. 225



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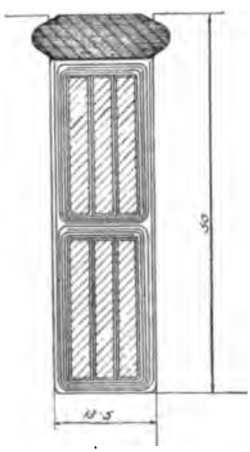
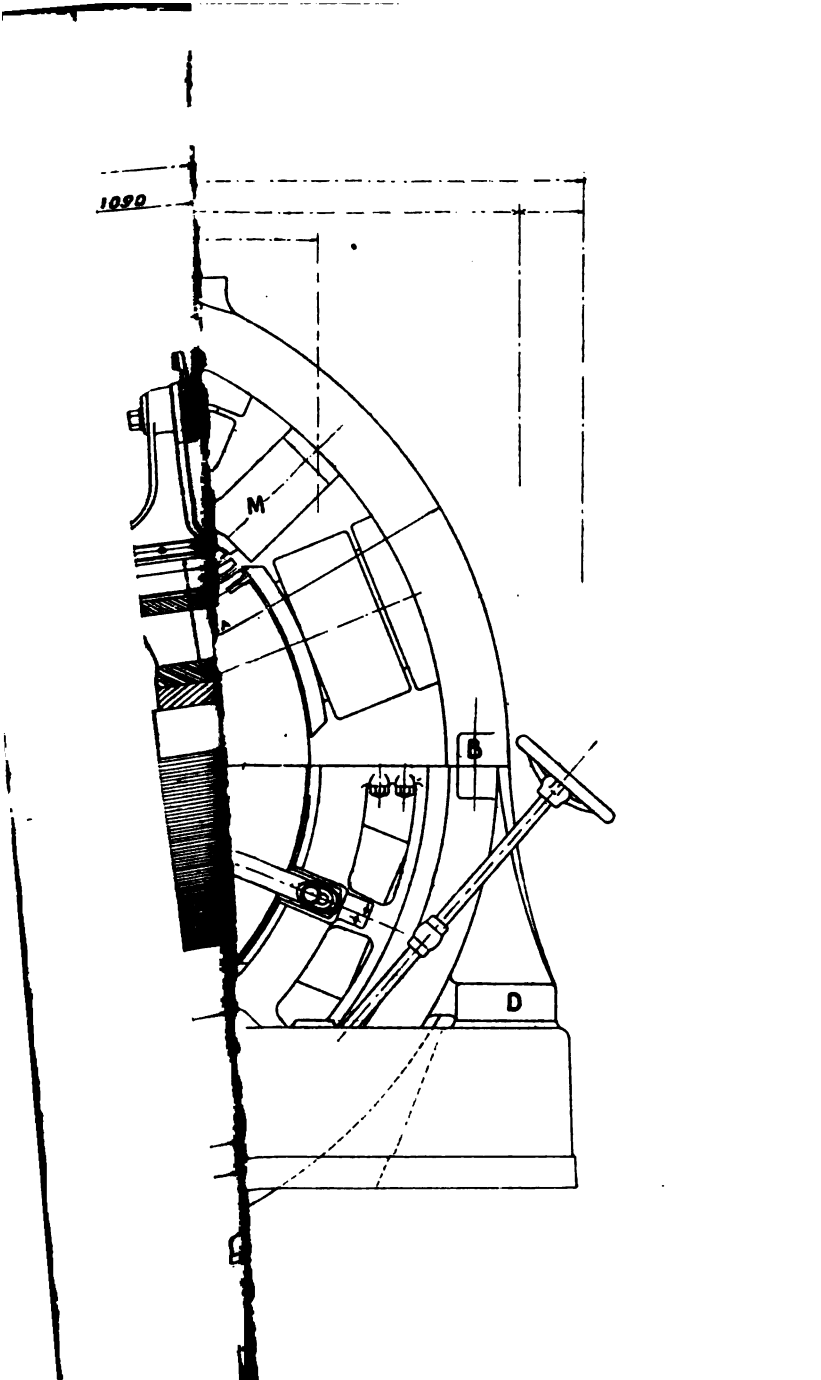
down to receive the commutator spider. The armature core plates, G, are of thin wrought iron and have 144 slots for the reception of the conductors, each slot carrying six conductors, the arrangement of which together with the method of insulation is shown in fig. 227. The armature winding is of the parallel type and consists of 432 coils, there being, as usual, the same number of commutator segments as there are coils.

Each armature coil has one turn, and thus there is a total of 864 conductors in the slots. The section of the conductors is found from the drawing to be about 47 sq. mm., and the current per conductor will therefore be about $\frac{1180}{8} = 147{\cdot}5$ amperes since the armature is parallel-wound. Consequently the current density is about 3·14 amperes per sq. mm. All the core discs are clamped firmly together between the two end-plates, H, by means of sixteen bolts, the discs being separated at six intervals to allow of ventilation. The core end-plates are provided with ventilation holes, and the rims serve as supports for the overhanging ends of the winding. These ends are bound in position by means of a number of turns of steel wire wound tightly round, and soldered together—a strip of mica being placed between the binding wire and the coils. The conductors are held in position in the slots by means of wedges as shown in fig. 227. The armature core is driven by means of a key in each arm. The manner of fixing the commutator segments can be seen from fig. 226. The segments are made of hard-drawn copper, and are insulated from one another by mica strips cut to the same shape as the segments. A wedge-shaped ring, K, at one end of the commutator spider grips the segments at one end, the other end being fixed by a steel wedge-shaped ring L, which is screwed on to the rim of the commutator spider. There is, of course, a good layer of mica and shellac

FIG. 227




1090
M
B
D

insulation between the segments and frame. There are eight sets of commutator brushes, every alternate brush being connected to one or other of two rings from which connections are taken to the two terminals of the machine.

It will be noticed that only one pedestal and bearing is shown, as the machine is supported at the other end by the coupling already referred to. Lubrication is effected by means of rings which ride loosely on the shaft and carry the oil up from the well into grooves provided in the white metal which forms the surface of the bearing. The wedge-shaped collars on the shaft are intended to prevent the oil from spreading to the outer side of the bearing cover. When necessary—that is to say, when there is any risk that any of the various nuts on the machine shall work loose in consequence of the vibration, they are effectively locked by means of Thackwray washers, which consist of springs or one or more turns of flat steel strip.

It has already been explained that, in order to obtain sparkless running, it is often necessary to give the brushes in the case of a generator such a 'lead' that the coil which is undergoing commutation may move in a magnetic field which assists in reversing the current in the coil, the field utilised in this case being provided by the main pole. It is, however, possible to provide this field by means of a magnet pole excited by a separate coil, the pole being placed in the space between two adjacent main poles, and excited by coils which are placed in series with the armature circuit. In this way a 'commutation field' is produced which varies more or less in proportion with the load. This is a very valuable feature, and in order to facilitate matters the induction density in the auxiliary poles is kept low.

The number of 'commutation' poles is generally made to equal the number of main poles, but it can be shown that the *necessary* number is only one in the case of a machine whose armature has a winding of the series type, while for a machine whose armature winding is of the parallel type the number of these auxiliary poles need only be equal to half the number of main poles. In the machine shown in fig. 226 the number of commutation poles is four, two of them being shown at M M.

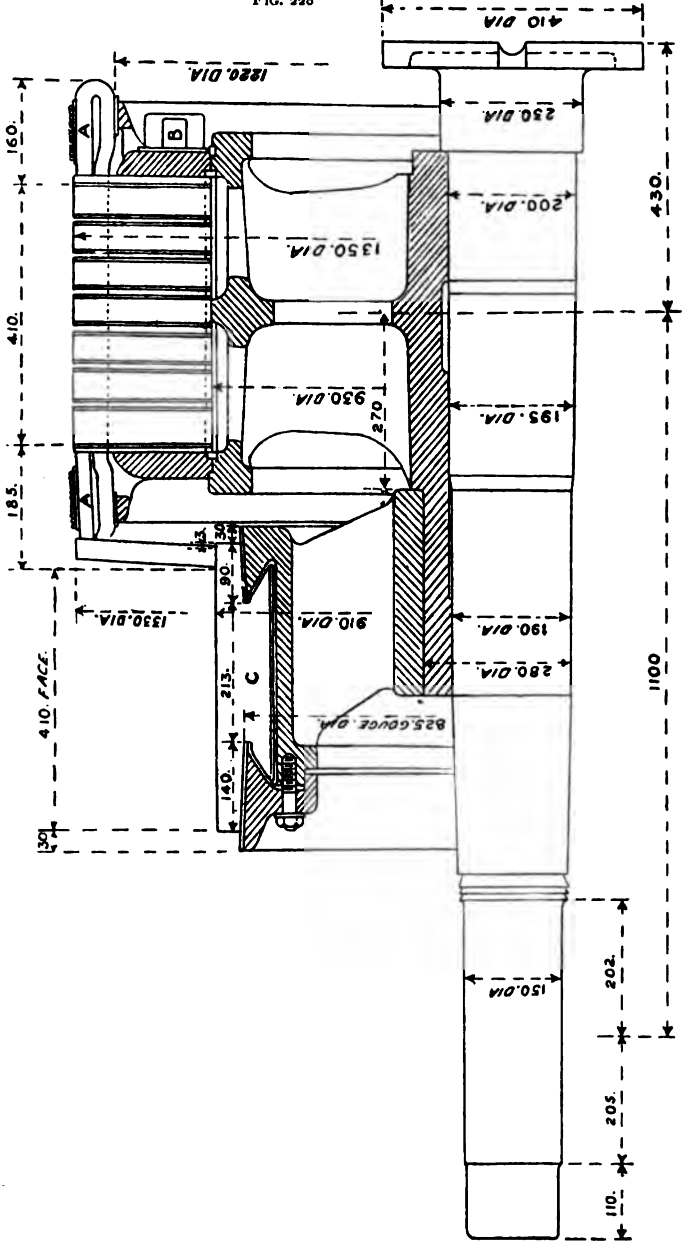
At N 'equalising' rings are shown which are connected at suitable points to the armature conductors, and serve to equalise the currents in the armature coils and thereby to maintain the machine in balance magnetically. While not attempting to fully explain the principle involved in this device, it may be pointed out that if it were not adopted an inequality in the magnetic balance would not only tend to make the shaft vibrate, but would result in the flow of possibly very heavy currents between the commutator brushes of the same polarity, which are, of course, all connected together. The sparking limits would consequently be considerably reduced.

In fig. 228 the construction of the armature core and commutator is shown in detail for a direct-current generator giving 600 kilowatts at 290 revolutions per minute. The core plates are built up in seven sets separated by ventilating ducts, and inside each duct there are two specially thick plates of sheet steel of about 1·6 mm. in thickness. One of these plates has distance pieces attached which act as wedges between the two thick plates and at the same time allow of the circulation of the air. There are 144 slots in the armature, each slot having four conductors, giving a total of 288 coils, and there is one coil per commutator segment. A sketch of a cross-section of one of the slots is shown separately in fig. 229. The separate conductors are insulated in the usual way and kept in position by a wedge of fibre. The armature winding is of the parallel type, and as in the larger machine, previously described, equalising rings, B (fig. 228), are provided for balancing purposes. The ends of the armature conductors, A A, are secured by means of tinned-steel wire. The substantial support for the commutator segments, C, and the method of securing them are also clearly indicated. A number of dimensions indicated in millimetres is included in the illustration.

It is customary to test the insulation of the commutator to the frame by fitting a metal ring tightly over the segments and connecting it to one terminal of a transformer (Chapter XIII.), giving about 2000–3000 volts, the other terminal being connected to the frame.

Details concerning another first-class multipolar machine,

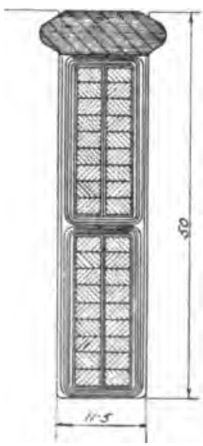
Fig. 228

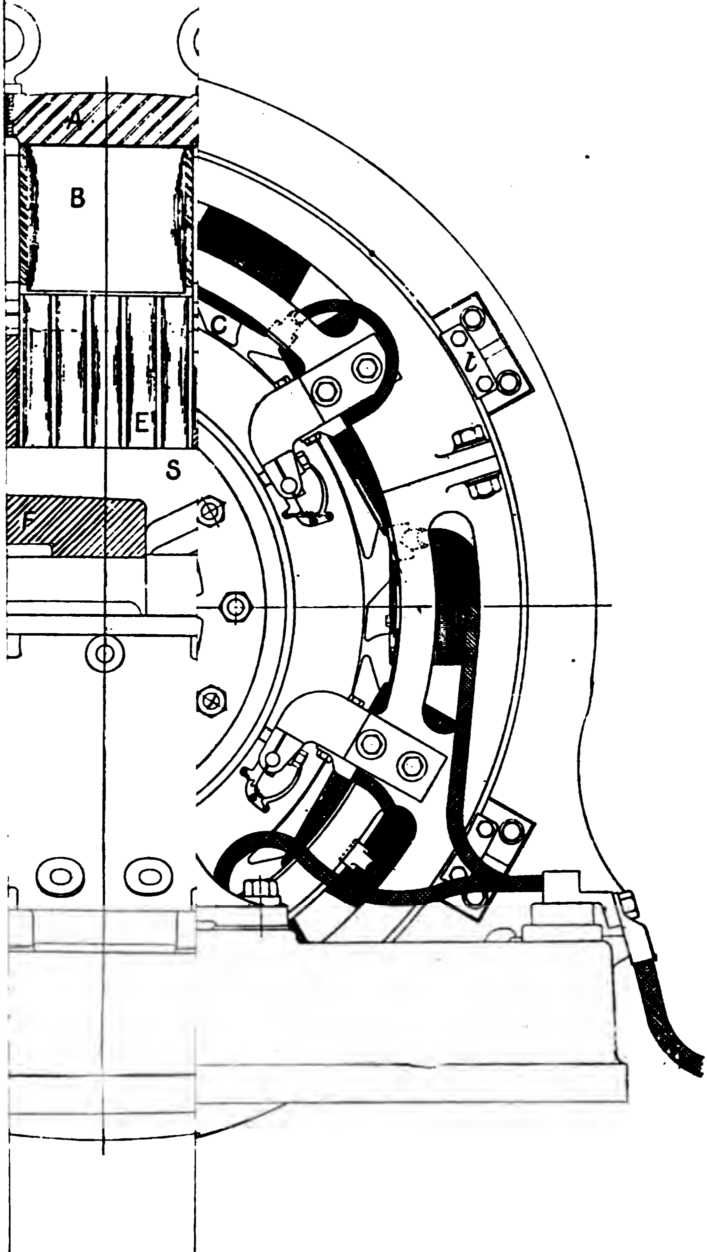

410 DIA
1220 DIA
250 DIA
200 DIA
1350 DIA
930 DIA
195 DIA
190 DIA
280 DIA
910 DIA
1330 DIA
825 GOUGE DIA
150 DIA
A
B
C
160.
410.
185.
430.
1100
270
410 FACE
213.
140.
90.
30
202.
205.
110.

designed in this case by Messrs. J. H. Holmes & Co., are given in figs. 230 and 231.

The magnet frame A is a ring of cast steel to which the main poles B and the commutation poles C are bolted. There are six main poles built out of soft-iron laminations, which are clamped together between two steel end plates. The field-magnet coils are wound in sections as shown at D, the sections being separated by pieces of wood and the whole taped together. The machine is compound wound, having both series and shunt field-magnet coils, the shunt coils being wound in two sections per pole. This enables the heat to be more easily conducted away, for the cooling surface is much greater than it would be if the coils were all wound continuously. Moreover, there is a space between the poles and the coils which allows a current of air to pass through and thus to satisfactorily ventilate the field winding. The particular machine illustrated had to satisfy rather stringent conditions as to the temperature rise of the various parts, and after a six hours' run at full load the increase of temperature of the field-magnets was only 41° F., which is exceptionally low. The commutation poles are six in number, and each pole is bolted to the frame midway between two consecutive main poles. A special feature of the auxiliary poles in this particular machine is the shape of the shoe, which departs from the usual practice in that it is skewed over towards the main pole of the same polarity as itself. Hence commutation is not allowed to take place with the brushes midway between the main poles, but the brushes are shifted forwards so that they short-circuit those conductors which lie near the leading pole tip of the main pole—that is to say, that pole tip which the short-circuited conductors are approaching. The object of this special form is to prevent a flash round the commutator when the load is suddenly changed. There are six sets of brushes, which are connected alternately to each of the copper bars L L, this being allowable because every

FIG. 229




A
B
C
l
E
S
F

alternate brush-set is of similar polarity. The armature has a 'wave' or series winding, and there are 93 slots in the armature core, each of which carries four conductors. Although it is possible, when this type of winding is adopted, to collect the total current from two brush-sets only, independently of the number of poles, it is nevertheless advantageous to provide as many brush-sets as there are poles, for, apart from the fact that the arrangement provides greater facilities for collecting the heavy currents, there is much less danger of sparking at the commutator.

All the coils of the commutation poles are joined in series, their extremities being connected to two rods which form the terminals of the machine. The armature core E is built up of soft-iron laminations collected together in five sections, each section being separated by distance fingers, thus allowing passages for the circulation of air, with the object of keeping the whole cool. The core plates are threaded on the arms S of the cast-iron spider, whose boss F fits on to the shaft. The end-plate T serves the double purpose of clamping the core discs together and providing a support for the ends of the armature coils. The external diameter of the armature core is 36 in., and the length of the core between the clamping disc is 9¼ in. The commutator spider fits on the boss of the armature spider, and the construction of the commutator will be clear from fig. 231, in which G indicates the ventilation passages through the body of the commutator. Each brush set consists of five carbon brushes, which are kept in position by springs. This provides a much more certain contact than can be obtained with a single brush, and allows for any slight unevenness in the wear of the bearing surfaces.

All the brush holders are screwed to the ring plate M (fig. 230), which is capable of being rotated through a few degrees by means of the hand wheel P. This ring plate is kept in position by six small plates *t* (fig. 231), which permit of the sliding of the ring M backwards and forwards in its grooves. The output of the machine at a speed of 375 revolutions per minute is 200 kilowatts at 550 volts, which shows that the full load current will be 364 amperes. After a six hours' run at full load in an atmosphere at a temperature of 59° F. the rise of temperature of the commutator was only 33° F., of the armature winding 39° F., and of the armature core 43° F.

We have already stated that the temperature rise of the field-magnets was only 41° F. These figures are exceptionally low, and in view of the fact that an all-round rise of about 70° F. is permissible, it should be evident that the machine could be rated at a considerably higher output in the ordinary way.

The winding of the field-magnets is compound and the resistance of each shunt coil is 18 ohms and of each series coil 0·00096 ohm. Since there are six coils, the total resistance of the shunt winding is 108 ohms and of the series winding 0·00576 ohm. The flux per pole is $8\frac{1}{4}$ millions of lines. Now from the formula already given for the calculation of the E.M.F. developed in a multipolar machine we can see how the E.M.F. of this machine can be found, for the E.M.F. *developed* is

$$\frac{\mathrm{NP}n}{10^8} \times \frac{p}{a}$$

in which $\mathrm{P} = 93 \times 4 = 372$ conductors; $\mathrm{N} = 8\frac{1}{4} \times 10^6$ lines; $n = \frac{375}{60} = 6{\cdot}25$ revs. per sec.; and, since the armature is series wound and there are three pole pairs, $\frac{p}{a} = 3$;

$\therefore$ E.M.F. developed

$$= \frac{8{\cdot}25 \times 10^6 \times 372 \times 6{\cdot}25 \times 3}{10^8} \text{ volts}$$

$$= 575 \text{ volts}$$

To obtain the terminal potential difference we must subtract from this, not only the pressure drop due to the current in the armature, but also the drop due to the current in the series-winding and commutation poles. The total resistance of these in series with one another is $0{\cdot}021 + 6 \times 0{\cdot}00096 + 6 \times 0{\cdot}001$ ohm

$$= 0{\cdot}021 + 0{\cdot}00576 + 0{\cdot}006 \text{ ohm}$$
$$= 0{\cdot}03276 \text{ ohm}$$

assuming the resistance of the commutation pole winding to be about equal to that of the series field winding. The pressure drop is therefore $364 \times 0{\cdot}03276$ volts $= 11{\cdot}9$ volts. Besides this there is a drop of about 2 volts due to the contact resistance of the

brushes. Hence the resultant terminal E.M.F. should be, according to this, about 560 volts. It must be remembered, however, that in calculating the E.M.F. developed we assumed that all the conductors were active; as a matter of fact, a little consideration will show that since about six conductors are short-circuited the net number of active bars is only about 366, and therefore the above obtained E.M.F. must be reduced in the ratio $\frac{366}{372}$, which gives the resultant available terminal pressure as 550 volts.

This machine is intended for direct coupling to an engine, and the whole arrangement is fixed to the bed-plate W. There is only one bearing, which is lubricated by rings, which fit into the grooves A A and dip into the oil below; the oil is therefore carried round with the shaft, providing a very efficient and satisfactory means of lubrication. The other end of the shaft is supported by the engine coupling.

The principle of direct coupling to steam turbines described in Chapter VIII. in connection with the turbo-alternator is also applicable to continuous current working, and much of what was said in respect to the special features of the turbo-alternator appertains equally well to the direct-current turbo-dynamo. In machines of the latter class, however, the field system is always stationary, and is often provided with commutation poles. Additional compensation windings are also usually provided, consisting of coils which are placed in specially prepared slots made in the pole-shoes, their object being to assist in neutralising the distorting effect of the armature current, and thereby to increase the facilities for satisfactory commutation.

A very noticeable feature in connection with the armature is its great length as compared with its diameter. As a matter of fact, each of these dimensions is in large machines made as great as circumstances will permit. The determining factor in the case of the diameter is the circumferential velocity, which must be kept within such limits as will avoid the risk of the coils shifting their position, while the length must be such that the potential difference between adjacent commutator segments shall not be too high, otherwise there will be the risk of the current flashing from segment to segment and from brush to brush round the

commutator. Fig. 232 illustrates an armature for a turbo-generator built by Messrs. Brown, Boveri & Co. for an output of 1500 kilowatts at a pressure of 550 to 650 volts, when running at a speed of 1000 revolutions per minute. The ventilation of the armature is effected in a manner similar to that described in connection with the rotor of a turbo-alternator, and the openings provided for this purpose at the end of the armature can be clearly seen in the figure. The rotor is carefully balanced by means of screws in the end caps, both before and after coupling to the turbine. Some of these screws are shown in the figure.

The commutator is exceptionally long, and in order to prevent the segments from flying out, steel rings are shrunk on at intervals,

FIG. 232

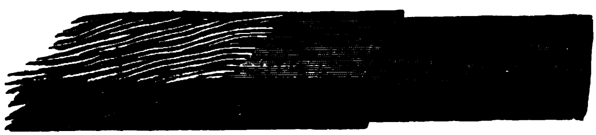
suitable means being, of course, adopted to adequately insulate these rings from the segments. A groove is cut in each of the rings, and steel plates of the necessary dimensions are screwed into them, in order to ensure that the commutator shall be perfectly balanced.

Several devices have been adopted by various manufacturers with the object of keeping the commutator cool. Sometimes a blast of air is directed on to the surface, but one device which has proved very satisfactory is to drill a number of holes in the segments parallel with the axis, and by a special arrangement of vanes to cause the air to be drawn right through the segments, with the result that they are effectively kept at a low temperature.

In concluding this chapter, we may with advantage make a few further remarks concerning the losses which reduce the effi-

ciency of a dynamo. Omitting the power absorbed in overcoming the conductor resistance, which can easily be calculated, the losses may be classified under three general heads: (*a*) mechanical friction; (*b*) eddies in conductor; (*c*) losses in armature core and pole-shoes. The friction occurs principally at the bearings—for the commutator brushes should exert only just sufficient pressure to ensure reliable contact—and the loss due to this cause increases regularly with the speed at which the machine is driven. In order to make the friction at the bearings as low as possible, care should be taken that the armature is perfectly balanced magnetically as well as mechanically, while the bearings themselves should be well designed and well made. A good lubricant should be employed, and should the accidental entrance of grit or dirt or any other cause give rise to undue heating, the bearings should be carefully cleaned at the first opportunity, and, if necessary, scraped.

FIG. 233



When the conductor is massive, as in the case of a bar armature, the eddy currents in the conductor itself may be sufficiently important to absorb a considerable amount of power, and, as we have seen, such conductors are frequently laminated, or sometimes braided wire is employed, to prevent the circulation of the currents. A form of laminated armature bar frequently employed is that shown in fig. 233. It consists of a number of bare copper wires twisted together and then compressed into rectangular bars. As the electro-motive force tending to set up the eddy currents is exceedingly feeble, very slight insulation suffices; the thin film of oxide with which copper becomes coated upon exposure to the air is sufficient, provided the pressure applied in compressing the wires has not been great enough for the wires to break through this film and make metallic contact; but, as a further precaution, the wires are usually coated with oil. The strands should not be

sweated at both ends, otherwise the advantage of stranding is liable to be annulled, since the induced eddy currents would then be able to make a complete circuit through the sweated ends.

Lamination of the iron core, if properly performed, also reduces to a minimum the eddies in the iron; but there is another source of loss which arises when lines of force passing through iron are rapidly reversed or altered in direction, due to the phenomenon known as hysteresis. This loss appears to be the result of a kind of internal friction between the molecules of the iron when they change their position, as we believe they do, under the influence of the magnetising force. At any rate, it is not possible to project lines of force through iron, or to alter their position, without a small amount of work being performed independently of that resulting in eddies.

This question has already been referred to at the end of Chapter VII., and it will be remembered that the energy lost by hysteresis per cubic centimetre of iron depends upon the value of the maximum induction **B** and also upon the coercive force of the iron employed. Thus, for one particular specimen of iron, when $\mathbf{B} = 18{,}000$, Dr. Hopkinson estimated that 13,000 ergs per cubic centimetre were expended in twice completely reversing the magnetisation, or in performing the complete cycle of operations as indicated by the curve in fig. 137. If iron of this description were employed for an armature core having a mass of, say, 1000 cubic centimetres, and if the flux corresponding to an induction $\mathbf{B} = 18{,}000$ were twice reversed, say 50 times per second, the energy lost by hysteresis per second would be $13{,}000 \times 1000 \times 50 = 650{,}000{,}000$ ergs. Since a loss of 10,000,000 ergs per second is equivalent to one watt, this would represent a loss of $\frac{650}{10} = 65$ watts.

As, however, any vibration to which the iron may be subjected assists in the changing in position of the particles under the influence of the magnetising force, and as the armature of a dynamo machine when running experiences considerable vibration, the losses due to hysteresis are in practice somewhat less than those calculated from experiments made with the specimen

free from vibration. The reduction in the hysteresis effect by vibration is, however, less when the induction is high, as in the case of an armature core, and in any case the small advantage accruing from this vibration does not in any way diminish the importance of selecting iron of low coercive force.

With a given number of lines of force in any armature core the loss due to eddy currents varies as the square of the speed of rotation, while the loss from hysteresis is proportional to the speed simply. The former result follows from the fact that when the speed is, say, doubled, the strength of the eddy currents is also doubled, and the resistance remaining constant, the power lost is proportional to the square of the current strength. The hysteresis loss, however, depends upon the number of times that the iron particles are completely rotated per second, and this effect varies simply with the speed at which the armature is rotated. We might also expect that the hysteresis loss would vary directly with the value of **B**, the intensity of the magnetic induction through the iron, but experiment shows that the loss increases at a much faster rate than this, although no definite reasons can be assigned to assist us in calculating the exact rate. Mr. Steinmetz has shown by experiment that the loss by hysteresis increases as the 1·6th power of the inductive density in the iron, or

$$\text{hysteresis loss} = \text{v}\, a\, n\, \mathbf{B}^{1.6} \div 10^7 \text{ watts}$$

when v is the volume of the iron in cubic centimetres, a the coefficient to be determined by experiment for the particular quality of iron, n the number of complete reversals per second, and **B** the value of the magnetic induction through the iron.

CHAPTER XI

DIRECT-CURRENT DYNAMOS (CONCLUDED)

In the armatures of the direct-current machines hitherto described, all the coils are connected together, and the junction of each adjacent pair is joined to a bar of the commutator. The whole of the wire thus forms a complete electrical circuit, independently of any connection which may be made, by means of the brushes, to the external circuit; and such armatures are frequently referred to as 'closed-coil' armatures. But there is another method of constructing an armature, in which the coils are kept quite separate, each coil having in the simplest form a separate two-part commutator, so that each commutator segment has only one end of one coil connected to it. Every coil is then open or disconnected at the commutator when the brushes are removed, and such armatures are known as 'open-coil' armatures. Direct-current machines for developing a high electro-motive force, say 2000 or 3000 volts, were at one time usually built with open-coil armatures, and although they have long since passed out of general use, such machines were frequently used for electric lighting in cases where the type of the lamps and their disposition were such as to require the transmission of a current of moderate but uniform strength through an external and comparatively high resistance. In a closed-coil armature the E.M.F. generated by every coil in any and every position, excepting at the moment when it is short-circuited by the brush, forms a part of the total E.M.F. of the machine and does its share towards urging the required current through the external circuit. On the contrary, in an open-coil armature the current is collected from a coil while it is in or near the position of greatest activity only, or while the E.M.F. induced in it is at or near its maximum, the coil

being thrown out of circuit during the time that it passes through the period of least activity. At the beginning of this latter period another coil enters the best position, and commences to feed the circuit. The coils may be wound either on the ring or drum principle, and in the former case the two coils at opposite extremities of a diameter are usually joined together in series, and may therefore be treated as one coil.

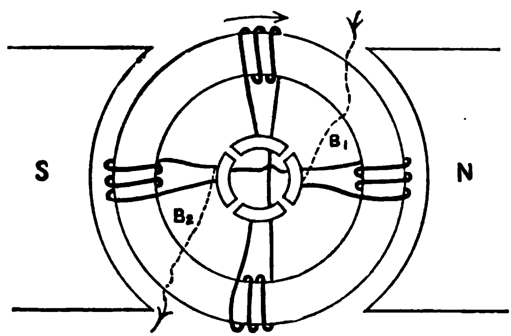
Many of the elementary principles examined in connection with the machines already described hold equally well for those with open-coil armatures, and while it is unnecessary to again enter into a lengthy discussion of these matters, we may say, briefly, that the field will be distorted in the same manner, and that the position of maximum activity for any coil will be that in which its plane is parallel to the lines of force of this resultant field. To minimise the distortion, and to obtain a high E.M.F. for a given speed of rotation, the field-magnets must in this case also be designed to maintain a powerful field.

The high E.M.F. developed requires, however, even greater precautions as regards insulation than are taken with ordinary closed coil machines, and this point must be kept in view in designing and selecting the materials for the insulation both of the armature and of the field-magnet coils. In closed-coil machines the maximum electro-motive force developed is as a rule comparatively low; and the potential difference between adjacent coils and commutator bars being only a fraction of the total potential difference at the brushes, the difficulties in the way of efficient insulation, even in cases where the machine is designed to produce a high electro-motive force, are not so great as might appear at first sight. But while in a closed-coil machine the number of active conductors joined in series between the brushes is never more than half the total number, in an open-coil machine the proportion is not only greater, being usually about two-thirds, but consists of those in the most active positions; and further, the total number of convolutions in the armature coils is much greater in order that a high E.M.F. may be obtained. Not only therefore must special precautions be adopted to secure effective insulation, but as the coils consisting of many convolutions are cut out of circuit while they are fairly 'active,' there must be some

means of dealing with the inevitable sparking; it must either be minimised by some arrangement of the commutator, or its destructive action prevented.

The fundamental principle of all open-coil dynamos is illustrated in fig. 234. Two pairs of coils are shown, wound round an iron ring, and placed at right angles to each other. The commutator has four parts, or, strictly speaking, there are two two-part commutators, and each of these two-part commutators is connected to the ends of its particular pair of coils. Two flat springs, B_1 and B_2, act the part of brushes. In considering the action of the machine we will, in order to simplify matters, assume that the field is undistorted. Since we desire to take the current from the

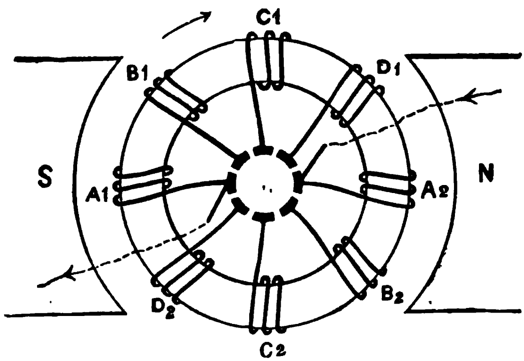
FIG. 234



coils while they are at their maximum activity, the brushes must be placed along a diameter parallel to the lines of force, a position exactly opposite to that of the brushes on a closed-coil machine. The two horizontal coils by this arrangement deliver their current to the external circuit, while the vertical ones, being comparatively idle, are entirely disconnected. The activity of the horizontal pair decreases as they move from this position, and when the armature has revolved through another 45° they are thrown out and the other coils begin to feed the circuit. Each pair is thus alternately joined up to and disconnected from the brushes for a period equal to a quarter of a revolution; and an ammeter placed in the external circuit would indicate a current always

flowing in one direction, but fluctuating considerably in strength. Greater steadiness—that is to say, a nearer approach in constancy—can be obtained by increasing the number of coils, although it is not possible to get a current so nearly constant as that which a good closed-coil dynamo can generate. In fig. 235 the number of coils is increased to eight, that is, four pairs. In every case the two coils at opposite extremities of a diameter (A_1 A_2, for instance) are joined together to form a pair as before; but to avoid a complicated diagram this connection is not shown, and the distortion of the field is again ignored. Each pair has its two-part commutator, the segments of which are (including the insulating space

FIG. 235

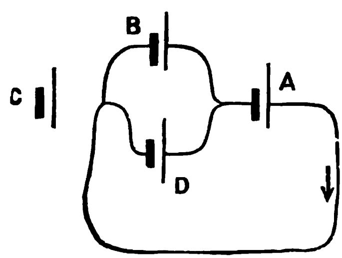


between the adjacent segments) one-eighth of the circumference of a circle in length, and therefore each pair of coils is connected to the brushes for one-eighth of a revolution only. If the strength of the field, the number of convolutions per coil, and the speed of rotation were the same as in the case just considered, the maximum electro-motive force developed would be the same; but as the minimum does not now fall so low during the time that the coils are connected to the brushes, the result is a more uniform current in the external circuit.

It will probably occur to the student that the coils D_1 D_2 and B_1 B_2, although much less active than A_1 A_2, are yet in a position where they can generate a considerable E.M.F. and that they might

with advantage be allowed to assist. But they must not be joined up *in parallel* with A_1 A_2, since their E.M.F. is so much lower. Were they to be so joined up we should get a result similar to that obtained when a Grove cell and a Daniell cell are connected in parallel, in which case the Grove cell would urge a backward current through the Daniell because it has a higher E.M.F., and the external circuit would therefore get actually less current than if the latter cell were removed altogether. But if the two are joined up *in series*, then the external circuit gets the whole current resulting from the sum of their two E.M.F.'s. In the same way, if the effect of the coils in positions of less activity is to be utilised, they must be joined up in series and not in parallel with those developing the higher E.M.F. We will explain how such an arrangement is effected in the Brush dynamo. Now in the case of a set of four pairs of coils rotating in a uniform field, as in fig. 235, it is clear that at one time only one pair of coils can be in the best, and only one pair in the worst, position for generating a current.

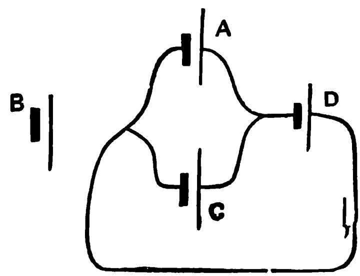
FIG. 236



On the other hand, it is possible for two pairs to be equally active in an intermediate position, and this will happen when they make an angle of 45° with the lines of force : that is, in the position occupied by B_1 B_2 and D_1 D_2. In the Brush dynamo, when the armature consists of eight coils in four pairs, two pairs of brushes are employed, one collecting the current from the pair of coils in the best position only, A_1 A_2, while the other joins up *in parallel* with each other the two pairs of coils, B_1 B_2, D_1 D_2, which are at the moment in the intermediate position, and collects the current from them. The two pairs of brushes are permanently joined in series, and thus the E.M.F. of the intermediate pairs of coils is *added* to that of the pair of coils in the best position, only one pair, as C_1 C_2, being thrown idle at a time. As the intermediate coils are placed in parallel their resulting E.M.F. is the same as that of one of them, the resistance being,

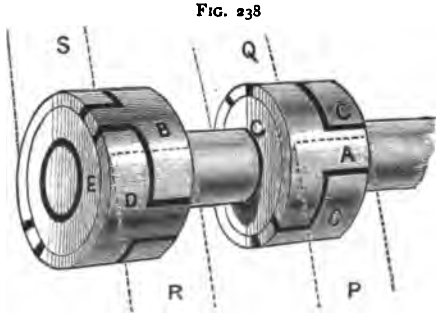
however, halved. In order to make this quite clear we may represent a pair of coils as we do a primary cell, and then show the arrangement, as in fig. 236, where A represents the most active, and C the least active pair of coils, B and D being those in the intermediate stage. When the armature has turned through another 45°, the B coils are idle, the D coils are in the position of maximum activity, and the A and C coils in parallel as shown in fig. 237.

FIG. 237



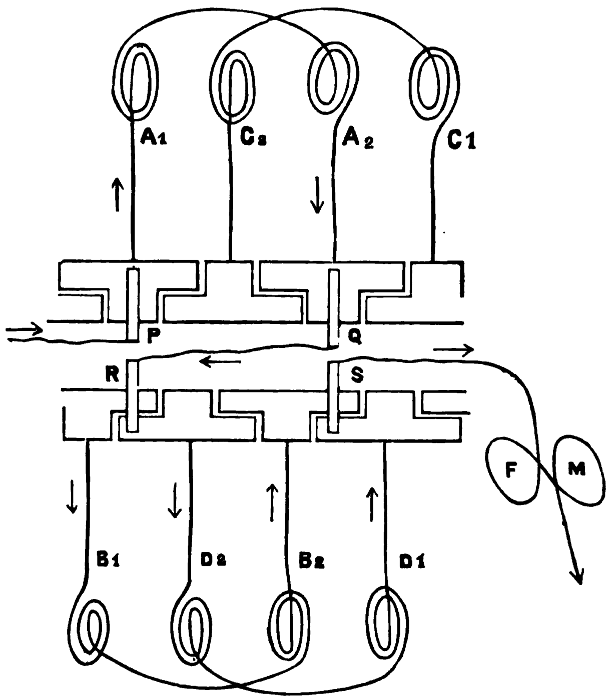
The commutator, by means of which these changes are effected, is illustrated in fig. 238. It is divided into two portions, each complete in itself, and consisting of four thick T-shaped pieces of brass separated from the shaft by rings of insulating material, E, G, the T-shaped sections being insulated from each other by air-spaces as indicated by the thick black lines. The brushes, P Q R S, are formed of flat copper strips, and, as shown by the dotted lines, are sufficiently wide to cover the whole width of the commutator rings. The ends of a pair of coils are joined to diametrically opposite segments or sections as indicated in the figure, the lettering in this illustration corresponding to that in fig. 235. One of the commutator rings is fixed on the shaft 45° in advance of the other, the consequence of which is that when, on one ring, each of the brushes is resting on one section only, as at A, then each brush on the other ring is in contact with two sections, as at B D. The student will perceive that

FIG. 238



in the case illustrated the sections of the left-hand commutator ring have joined to them the two pairs of coils which are for the moment in the intermediate position, and therefore require to be placed in parallel; while the right-hand ring has joined to it the pair (A) which is in the best position, and also the pair (C)

FIG 239



which, being inactive, is entirely disconnected from the brushes and the external circuit.

In fig. 239 the two double commutators are developed or spread out, side by side, to make the matter clearer, the lettering of the coils being the same as in fig. 235. The path of the current can be easily traced. It first passes round the pair of coils, A_1 A_2, the brushes P and Q (by which it enters and leaves) each resting on one

section only, because those coils are in the best position. The current then passes direct to the brush R (on the left-hand part of the commutator), which, resting on two sections, affords a path through B_1 B_2 and D_2 D_1, in parallel. The brush S, by which the current finally leaves, is connected to one end of the field-magnet coils, F M; the coils C_1 C_2 are disconnected. Such is the action which takes place in a Brush dynamo having four pairs of coils in its armature.

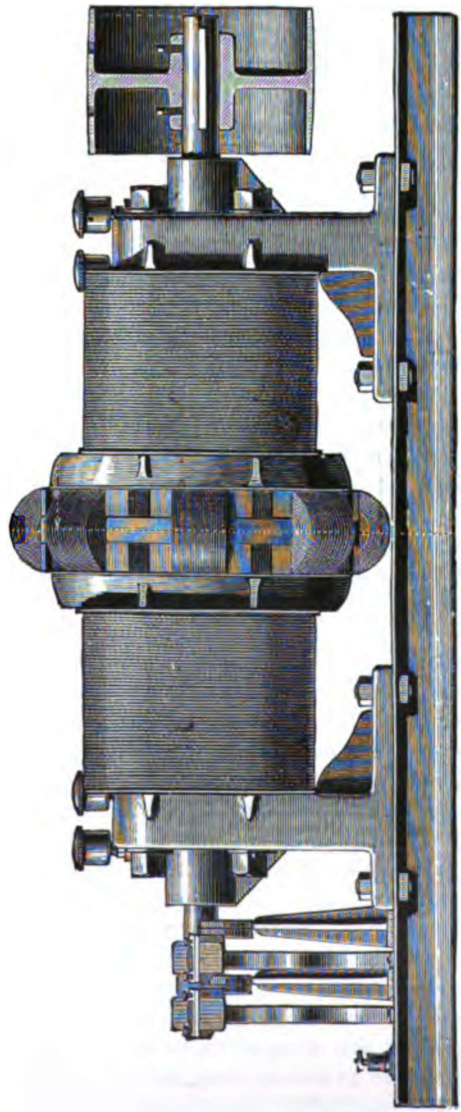


FIG. 240

The actual machine is depicted in fig. 240. The cores of the field-magnets are almost oblong in section, and are bolted to cast-iron uprights which form the yokes.

The two horizontal horseshoe field-magnets thus formed are placed with their similar poles opposite each other, and project a powerful field round the armature, half the lines of force passing through the core above the shaft and the other half below it, somewhat similarly to the case of a two-pole closed-coil machine with a ring armature. There is an unusually large quantity of iron in the armature core, and careful lamination is needed to reduce the loss of energy due to eddy currents.

The armature coils are insulated from the core by sheets of canvas and paper, treated freely with shellac varnish, the layers of wire being insulated by cotton cloth. The ends of each pair of coils are carried along the shaft to their proper sections of the commutator.

The field-magnet coils are insulated from their cores by vulcanised fibre and varnished paper, the different layers being separated, as in the case of the armature, by cotton cloth. These coils are joined up in series with each other and with the armature, and as the current generated by the machine fluctuates more or less, there is a tendency for eddy currents to be induced in their unlaminated cores. This tendency is overcome by the simple device of interposing between the coils and the iron a tube of thin sheet copper, in which the currents are induced instead of in the iron. These induced currents by their reaction upon the field-magnet coils tend to reduce the fluctuations of the primary current, and the high self-induction of the field-magnets and armature also tends to prevent any sudden variation of current strength, so that the resulting current is always more regular than might be expected from a consideration of the manner in which it is collected.

The pole-pieces are extended so as to embrace an unusually large portion of the armature, and the opposite or facing pole-pieces being similarly magnetised, the lines of force are not projected axially through the armature, but entering the core on both sides by the projections provided for the purpose, they tend to pass circumferentially round a portion of the core and leave it at another set of projections, near the other poles. The lines of force are in this way urged through and cut by the coils as they rotate, somewhat after the manner described in dealing with the

De Meritens alternator. The maximum induction in the armature core is considerably greater and that in the field-magnet core somewhat less than obtains in ordinary low-pressure closed-coil dynamos.

As the machine is regulated to give a constant current, the reaction of the armature on the field, and therefore also the lead of the brushes, varies only slightly under ordinary changes in the load. The current taken from the armature has practically the same value under all circumstances; but, as will be seen presently, the regulation is effected by shunting part of the current from the field-magnet coils when a lower electro-motive force is required, and consequently as the field varies somewhat in strength as the load changes, the reaction of the armature on the field is not constant. The adjustment of the brushes thus necessitated is usually effected by hand, but occasionally it is performed automatically, the rocker carrying the brushes being shifted into the correct position by an electro-magnet.

When the brushes are in the correct position it is not even then possible to altogether avoid sparking, and for this reason the commutator wears out much more quickly than does that of a closed-coil machine. It is, however, so constructed that any one or more of the segments can be readily, and at a comparatively small expense, replaced, and the sparking is thus rendered a not very serious matter.

The machine illustrated was designed to supply 55 arc-lamps in series, with a current of 10 amperes, the speed being 800 revolutions per minute and the maximum E.M.F. about 2750 volts. The principal dimensions are: length of bed-plate 7 ft. 10 in., width 2 ft. 5 in., height of highest point 3 ft. 1½ in., outside diameter of armature 2 ft. 9 in. The diameter of the shaft is 2¾ in., its centre being 1 ft. 9¼ in. above the floor line.

Although such of these dynamos as remain in use are mostly employed on arc-lighting circuits where a current of 10 amperes is required, a different current strength is sometimes desired, and a machine such as that under consideration can, without much trouble, be altered to give a current of 20 amperes with half the electro-motive force developed when 10 amperes are being obtained. To effect this change it is necessary in the first place to

connect every diametrically opposite pair of coils in parallel instead of in series, and secondly to join the four field-magnet coils in two sets of two in parallel instead of all four being in series. It will be observed that after this change has been made, every armature coil and every field-magnet coil carries a current of 10 amperes as before; the strength of the field remains unaltered, because we have half the E.M.F. applied to half the number of coils in series, but the number of armature convolutions joined in series is halved, and therefore the resulting electromotive force is also halved.

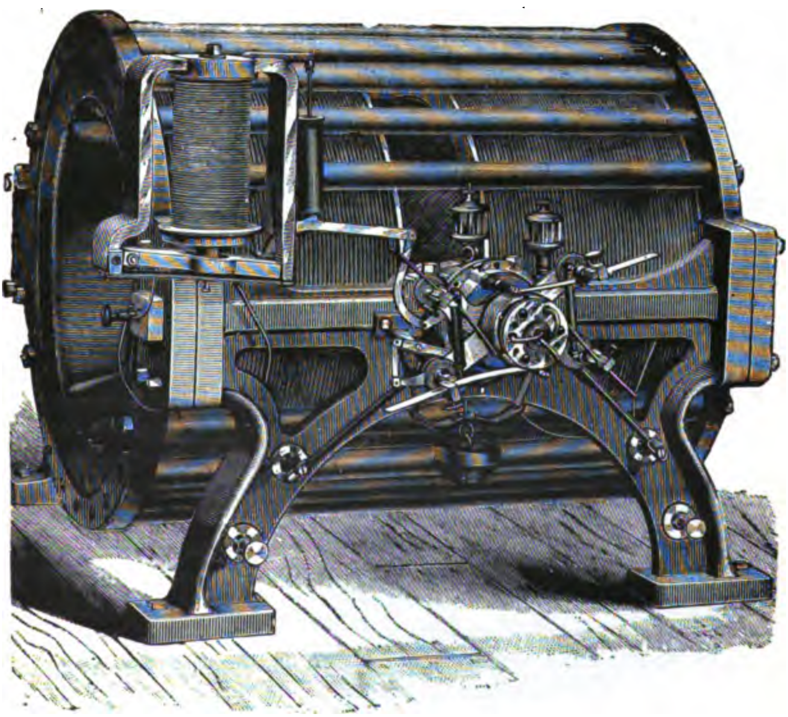
The brush holders are connected to terminals on the bed-plate by means of flexible copper strips, and each pair is carried by a rocker which can be turned for a limited distance round the shaft.

Although this machine is capable of supplying as many as 55 arc-lamps joined in series as its maximum load, the number of lamps actually switched in circuit may vary considerably from time to time; but the act of switching out a lamp by short-circuiting it, reduces the external resistance, and the machine being series-wound the current strength is then correspondingly increased. It is nevertheless essential that under all conditions the same current strength—viz. 10 amperes—should be maintained; hence some regulating device becomes necessary. The regulator devised for this purpose consisted of columns of thin retort carbon plates placed in series and connected as a shunt to the field-magnet coils. Two solenoids in series with the main current acted on a horseshoe-shaped core which was sucked in, or partially released from the solenoids according to the variations of the main current, and by this means the pressure on the carbon columns was varied, thus increasing or decreasing the resistance of the shunt and correspondingly the current in the field-magnet coils.

As might be expected, the efficiency of the Brush machine, and indeed that of any open-coil dynamo, does not compare favourably with that of a good low-pressure closed-coil dynamo. The commercial efficiency of Brush machines—that is to say, the ratio of the electrical power available for use in the external circuit to the power applied mechanically—may be taken at about 60 per cent. In order to effect any great improvement on

these figures it would probably be necessary to so alter the design of the machine that its distinct peculiarities which fit it for its particular work would be lost, and this loss would not be compensated for by the gain in efficiency. The machine will stand far more rough usage, and far greater stresses due to sudden changes in the load, than will an ordinary highly efficient closed-

FIG. 241



coil dynamo (in fact, no machine of the latter class could use up so much energy internally and survive); its high self-induction is more beneficial than baneful, and with its regulator a current sufficiently constant for the purpose can be relied upon.

The only other form of open-coil dynamo we need refer to is the Thomson-Houston, of which a view is shown in fig. 241. It is a

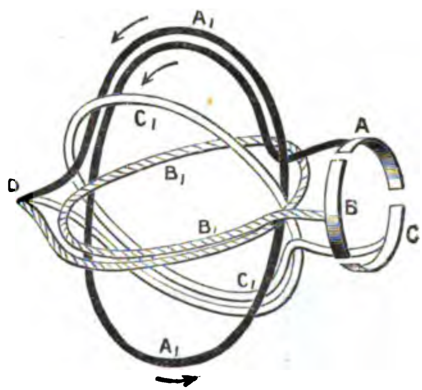
machine by itself, having many peculiar features, altogether different from those of any other with which we have dealt. There are two field-magnets placed horizontally, with their opposite poles facing each other. There is comparatively little iron in the cores, each of which consists of a cast-iron tube flanged at both ends, and provided at the armature end with a spherical cavity to form the pole-piece. The shape of the armature itself is that of a slightly flattened sphere, somewhat like an orange, and it revolves between and partly within the cup-shaped pole-pieces. The wire on each field-magnet core is wound in the space between the flanges, the outer flanges of the two cores being deeper than the inner ones, and affording, thereby, means for a number of wrought-iron bars to be bolted through them. These bolts add materially to the mechanical strength of the machine, protect the coils from injury, and form the yoke of the field-magnets. The machine which, on account of the small quantity of iron employed in its construction, has but little weight, is supported by comparatively light but strong standards, which are bolted to lateral projections from the flanges of the field-magnet cores. The standards also carry the armature bearings.

The manner in which the armature core is built up is also interesting. Upon the shaft are keyed two stout cast-iron discs, each provided on its inner face and near its periphery with an annular groove. About a dozen wrought-iron ribs are sprung into the pair of grooves, so as to bridge the space between the discs and form a circular framework, round which a number of layers of varnished soft-iron wire are wound. This forms the complete core into which, however, a number of wooden pegs are fixed, to guide the winding of the coils and to hold the wire in position. Before the coils are wound on, the core is insulated by layers of paper fastened by means of gum-lac.

The armature consists of only three coils, and fig. 242 illustrates, in the simplest manner, the way in which they are wound. The inner ends of the three coils are soldered together, as at D, and the junction carefully insulated. Starting from this junction, each coil is wound over the core, with an angle of 120° between the middle portions of the coils, the three free ends being joined, one to each segment, A, B, or C, of the three-part commutator.

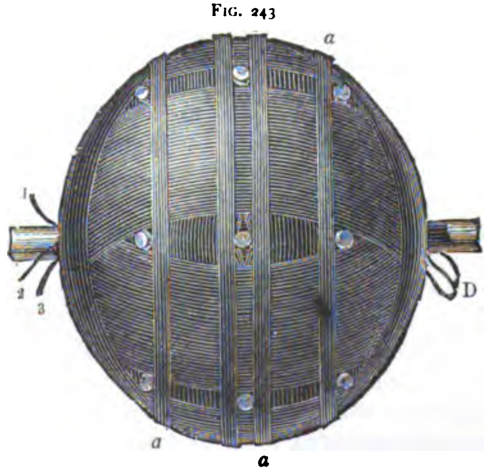
A view of the completed armature is shown in fig. 243, and it will be observed that the overlapping of the coils near the shaft causes the form to become almost spherical. The junction of the three coil-wires is shown at D; the free ends 1, 2, 3, being brought out on the other side of the armature. The coils when finished are bound round at four places with binding wires, *a a*.

FIG. 242



It is essential that every armature should be truly balanced, not only mechanically, but also electrically—that is to say, all the coils should be of the same area and equidistant from the core and pole-pieces, so that the inductive effect on each is precisely the same, and they should be all of the same length and of the same resistance. It is evident, therefore, that it would be inexpedient to wind the three coils in this spherical armature completely one over the other. But the length and the average distance from the core of all the coils is made equal by a very simple method of winding. Starting at the junction D, half of

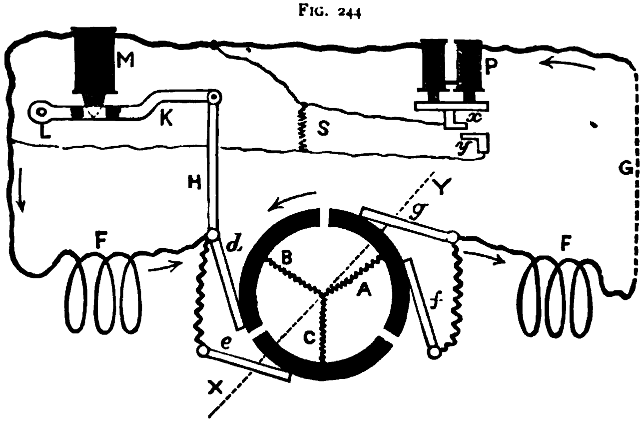
FIG. 243



one coil is wound; then, 120° further round the core half of the second coil is wound; yet another 120°, and the *whole* of the third coil is wound. The second half of the second coil is then wound over its first portion, and finally, the remainder of the first coil is wound over the corresponding first portion.

When the armature is rotated, currents, alternating in direction, are induced in each of the coils; the reversal, as usual, taking place in each case when the plane of the coil is at right angles to the lines in the resultant field. The reaction of the armature, of course, distorts the field somewhat, and shifts it round through a certain angle in the direction of rotation, as shown by the dotted

FIG. 244



line X Y in the lower part of fig. 244. In this figure each radial line, A, B, C, represents one of the armature coils, the three coils being united at the centre and each one joined to its respective commutator segment. The current is collected along the diameter of maximum activity, X Y, by two pairs of brushes, *d*, *e*, and *f*, *g*, each pair being electrically connected. The two brushes forming a pair are normally so placed that one presses on the commutator at a distance equal to 60° in front of the other. The consequence of this arrangement is that the most active coil is joined up in series with the remaining two less active coils, which are themselves joined together in parallel. In the case shown in fig. 244,

the coil A is approaching the best position; while B and C are in the intermediate stage, and are therefore joined in parallel. The resulting E.M.F. is, consequently, that due to the mean E.M.F. of B and C, added to the separate E.M.F. of A. As the armature rotates, B approaches the best position, and its commutator segment alone is then in contact with the brushes *d*, *e*, while C and A, which are brought to the intermediate positions, are joined in parallel. These changes are continually repeated as the coils pass through the different portions of the field.

As in the case of the Brush dynamo, this machine being series-wound and used on a circuit of high resistance for supplying a large number of arc-lamps joined in series, the switching out of any of the lamps tends to cause an increase in the current strength, while, conversely, the switching in of lamps causes a diminution. Hence, in order to keep the current at a nearly constant strength, some regulating device is necessary. The method adopted consists in simply altering the position on the commutator of the two brushes forming each pair. It will be observed from the commutator in fig. 244, that, the brushes being 60° apart, no coil is thrown out of circuit at any part of the revolution, and this is what we may call the normal state of affairs. When, however, the current falls in strength, each pair of brushes is closed up automatically, so that all the coils are, in turn, disconnected for a moment when they are passing the neutral position, and when they are, therefore, nearly idle. The E.M.F. of the two coils in parallel being the mean of their individual E.M.F.'s, it is, obviously, lowered when one of them is a comparatively idle coil, so that, at the moment when this idle coil is thrown out, the E.M.F. resulting from the other of the two coils in question is greater than it would be were they both in parallel. If this closing up of the brushes were to take place, then, when the armature is in the position shown in the figure, the comparatively inactive coil B would be disconnected, and A and C joined to the external circuit in series. The maximum E.M.F. would be developed when each pair of brushes is so closed up as to form practically one brush, in which case the least active coil would be always out of circuit and the other two joined up in series. From this point any opening of the brushes puts two of the coils in parallel for a greater or less interval of time,

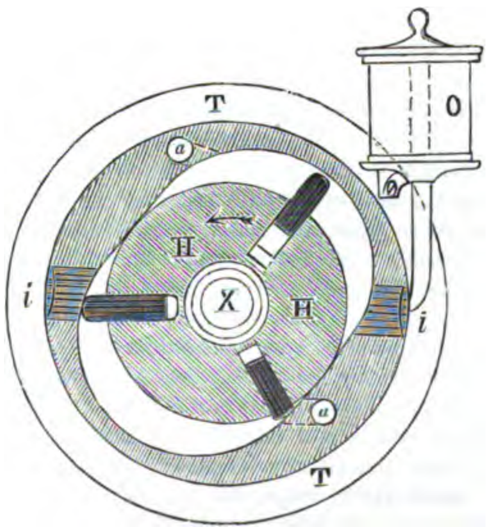
and reduces the resulting E.M.F.; therefore when the current becomes abnormally strong, the brushes are opened until the E.M.F., and, consequently also, the current, are reduced to the required value. The motion given to the brush-holders by the regulator is such that the following brush of each pair travels three times as fast as the leading brush.

The brushes *d*, *e*, *f*, *g* are mounted on a double lever, having a scissors-like movement about a common centre. The end of the lever carrying the brushes *d* and *f* is connected by the bar H to the armature K, under the electro-magnet M. This armature is hinged at L, and when the current in the main circuit becomes excessive, K is attracted, *d* and *f* are drawn back over the commutator, while *e* and *g* are pushed forward by a simple combination of levers not shown in the figure. The electro-magnet M and the double solenoid P are both in the main circuit with the field-magnets F F and the lamps in the external circuit G; but normally M is short-circuited by wires whose circuit may be broken at *x y*. The contact *x* is attached to the yoke of the two cores of the solenoids, and the first effect of an increase in the current is to raise the cores, break the contact at *x y*, and so cause the whole of the current to pass through M, which then attracts K and opens the brushes. A high-resistance carbon shunt is inserted at S to minimise the spark at *x y*. It will be noticed that the end of the core of M is shaped somewhat peculiarly and fits into a corresponding cavity in its armature; this shape is calculated to diminish the force of attraction uniformly as the armature recedes from the core. The regulating apparatus is shown in position in fig. 241. The small cylinder to the right of the electro-magnet is a dash-pot for steadying the movements of the lever.

There is one other device pertaining to the Thomson-Houston machine to which a reference is necessary; this is employed to suppress the excessive sparking caused by cutting out the coils when fairly active, which would otherwise speedily destroy the commutator. The segments are separated by air-spaces, and just in front of each leading brush is placed a nozzle which delivers a strong blast of air at the moment that the brush breaks contact, and so prevents the passage of the spark. The automatic

'blower' by which these timely puffs are delivered is shown in section in fig. 245. A circular steel hub, H, is keyed on to the shaft X, and revolves left-handedly in an elliptical chamber in the fixed box T T. Air enters this chamber through the apertures at *i i*, which are protected by wire-gauze coverings. The hub H is provided with three radial slots, in and out of which the rectangular ebonite slips can slide freely. As the shaft rotates these slips fly outwards by centrifugal force, and, pressing continually against the walls of the chamber, force the air in front of them, and out at the holes *a a*. To each of these holes is connected one of the two nozzles above referred to. The chamber is fixed to the framework of the machine in the necessary position for the maximum force of the blast to take place at the right moment. O is a vessel from which oil passes into the elliptical chamber through the aperture *i*.

FIG. 245



The machine illustrated is designed to supply a current of about 9½ amperes to 34 arc-lamps in series. The armature is

2 feet in diameter, over all, and the resistance of the field-magnets and of the armature is in each case 10½ ohms.

In addition to the dynamos which have been described in this and the preceding chapters, there are others to which the scope of this work has not permitted us to refer, although some of them are well worthy of study. We believe, however, that quite enough has been said to give the student a good insight into the science of dynamo-building as it is now practised. Where we have given sectional views or working drawings, they have for the most part been specially prepared for this work, and we have selected for such illustration those machines which we consider are best suited to show the manner in which theoretical principles are practically applied.

A comparison of these chapters with the corresponding chapters in the earlier editions of this work will show that the modern trend in dynamo design is towards simplification and uniformity of detail. As an example of the latter, we may cite the construction of commutators, in which the materials now employed are nearly always exactly alike, while in the manner of building up the parts so as to prevent the sections flying out there is very little real difference to be found. This similarity is what might, perhaps, have been anticipated; for, if the vast number of experiments which have been performed by the various manufacturers to determine which is the best appliance to perform a given kind of work have been equally exhaustive and accurate, an almost identical result should have been arrived at. Thus, no metal has been found superior to hard-drawn copper for the bars of a commutator, while for the extremely difficult task of satisfactorily insulating these bars in the case of a closed-coil machine, nothing has been discovered which approaches mica; indeed, were this mineral not available, it is probable that some alteration would have had to be effected in the general design. Among its many other useful properties which render it suitable for insulating commutator bars, mica resists abrasion to about the same extent as hard-drawn copper, and consequently it is worn down by the brushes at practically the same rate as the bars themselves. Great things were at one time expected of asbestos for insulating purposes, but it proved to be a good absorbent of oil and was

charred by the sparking, while the adhesion of metallic particles abraded from the bars and brushes soon developed a greater or less amount of short-circuiting with its concomitant evils. A somewhat similar result attended the use of simple air-spaces for insulating the bars, for the metallic dust or scrapings accumulated sooner or later at the bottom of the spaces, which, being numerous, were necessarily narrow. Occasionally a special form is given to a commutator; as, for instance, when it is built against the end of the armature, the individual bars being disposed radially. The object here is to reduce the length of the machine.

Much might be said upon the subject of brushes. In the early days hard brass or copper strips were very much in vogue. These were succeeded by copper gauze brushes, which in many cases gave way to a mixture of copper and carbon, but carbon pure and simple is now very extensively used for the purpose. A carbon brush if properly made and mounted wears slowly and evenly. It glides over, rather than rubs against the commutator, so that the wear of the bars is reduced. There is very little carbon dust scattered about the machine, whereas it was at one time no uncommon thing to see a machine more or less covered with metallic dust from both the copper brush and the commutator. It is in the power of an unskilful attendant to do much damage with a copper brush by pressing it too tightly upon the commutator and thereby prematurely short-circuiting a coil as well as unnecessarily scraping the bars away. With a carbon brush the area covered is determined by the cross-section of the brush, and no amount of pressure can affect it. Lastly, it is found that the effect of a carbon brush is to impart a smooth, even, highly polished surface to the commutator bars and to render altogether unnecessary the practice of rubbing the commutator over with an oily rag. The dark colour assumed by the bars is no doubt due to the presence of a small quantity of carbon, and doubtless some particles adhere to the mica insulation. But the consequent trouble is not nearly so marked as when copper brushes are used, the reason being in all probability that the quantity of carbon is less, and that the resistance of that substance is so much higher than the resistance of copper.

There is a type of generator known as the homopolar machine, by means of which a direct current is produced without the use of a commutator. In such a machine the armature conductors always move in a field of the same sense, and the E.M.F.'s being therefore always induced in the same direction do not require to be commutated. Such a machine is, however, very much heavier than one of the ordinary heteropolar type for the same output, voltage and speed, one reason of this being, that it has not hitherto been found possible to wind the armature so that the E.M.F.'s induced in the conductors assist one another. Therefore, in order to produce a moderately high E.M.F. it is necessary to connect each armature conductor to a separate pair of slip-rings, and by means of brushes bearing on these rings, the conductors are joined up in series by wires lying outside the range of the main field.

The General Electric Company of America have made such a machine for an output of 300 kilowatts at 500 volts and direct coupled to a steam turbine running at 3000 revolutions per minute. The armature has twelve conductors connected respectively to twelve pairs of slip-rings. The brushes used to collect the current from the slip-rings are of copper, and there is thus a great deal of wear at the high speed at which the machine runs—the peripheral speed of the rings being about 166 feet per second.

The lamination of the core of an ordinary ring or of a drum armature is a matter upon which little doubt now exists, for it is as certain as it well can be that the magnetic resistance should be kept as low as practicable, a result only to be arrived at by retaining metallic continuity in the direction of the lines of force: while, on the other hand, the lamination must be carried far enough to sufficiently reduce the eddy currents, every effort being made to make the quantity of iron as great as possible by using extremely thin insulation. Nothing better, therefore, can be devised than a core of thin iron plates of high permeability, separated by the thinnest possible layer of insulating material, the only doubtful point being the thickness of the plates. The thinner the plates are made, the more is the loss of power due to the generation of eddy currents reduced, but the proportion of space occupied by the insulating material and the expense of construction

are correspondingly increased. It is, perhaps, not possible to state definitely what the exact thickness of the core-plates should be for any given case, although as a general rule a thickness of 0·5 mm. is now adopted; but it can be safely said that it is always economical to reduce the hysteresis loss as far as possible, by adopting the only known course of experimentally selecting for the core-plates iron of the lowest coercive force. Experience has also shown that when the air gap is small it is imperative to laminate the pole-shoe in order to keep within limits the losses which would otherwise be caused by the slotted armature.

With regard to closed-coil armatures the drum form has been proved so superior from the point of view of the manufacturer, that it is practically the only type at present on the market. This is chiefly due to the fact that a drum armature can be wound so much more quickly and satisfactorily than a ring machine; the coils being wound on a former, insulated, and slipped into position in the slots with great ease and symmetrical perfection. Emphasis has been laid on the fact that in the case of a ring armature the 'spider' which carries the laminations for the core must be either partly or wholly of some non-magnetic material, such as gun-metal, in order to prevent leakage across the inside of the ring. It will be remembered that any such leakage results in inevitable loss, owing to the fact that an electro-motive force will be set up in the conductors, on the inside of the ring, and that this E.M.F. will be in opposition to the main E.M.F. developed in the outer conductors. The superiority of the drum armature having been established, the sphere of competition has been restricted, and this has caused manufacturers to avail themselves of every possible opportunity for reducing the cost of production of this particular type of armature. One result is that, whenever it is possible, materials are used which can withstand high temperatures, and the various parts are designed to run when fully loaded at higher temperatures than were deemed safe in bygone days. The field-coils are in some cases allowed to rise to a temperature of about 80° F. above the surrounding air, and this value is nearly twice that attained a few years ago. It is, however, necessary to make sure that while one part of the machine is allowed to work at its extreme heating limit, another

is not running comparatively cool. This inequality of working temperature in the various parts of a machine was in the early days a noticeable defect in the design of machines generally.

Up till quite recently the limit of the output of many machines was fixed by the sparking at the commutator becoming excessive before the heating limit of the armature was approached, and the most marked advance in the design of direct-current machines has been to limit the output of a machine by the temperature rise. This has been brought about by means of improved commutation and a consequent diminution of sparking, and has led to the reintroduction of commutation poles excited by coils in series with the armature and which produce the field necessary for commutation without giving the brushes a lead. The result has been a very great increase in the capacity of machines, and the method is now adopted very generally for almost all sizes of machines. A further device for improving the commutation properties of a machine is the provision of special windings on the field-poles which counteract the effect of armature reaction. These windings are placed in slots in the pole-shoes, and the main armature current is led through them, the direction of the current being such that the distorting field produced by the armature is more or less neutralised. It is doubtful indeed whether the turbo-generator would have been feasible were it not for the forced commutation which is effected by the commutation poles, or for the adoption of compensating windings to counteract the effect of the armature reaction. Considerable attention has also been devoted to the composition of the brushes with the result that a number of types are now available, into the construction of which carbon enters very largely, and which have been designed more or less in accordance with the theory of commutation. Thus a type of brush known as the Endruweit has thin skins of copper running in a direction perpendicular to the bearing surface of the brush, in order to diminish the resistance of the brush in this direction, without at the same time lowering the resistance in a direction parallel to the direction in which the commutator bars are moving. The degree of hardness of the carbon has naturally a considerable influence upon the sparking properties of a machine.

We have already pointed out that the bi-polar machine is practically a thing of the past, and as regards multipolar machines, the Schuckert and other 'flat ring' armatures described in earlier editions of this book have been relegated to the domain of history and have given place to machines of the radial type, similar to that shown in fig. 228. The old horseshoe type had the disadvantage of being difficult to make, had a large amount of leakage, and was very heavy in proportion to its output. The Manchester type is more symmetrical, but this is practically obsolete on account of its leakage and of its weight per unit of output.

It will be clear from what has been said that in designing a successful and economical machine which will satisfy modern requirements it is necessary to carefully consider every detail of the design so that all the material may be worked to its fullest capacity and the cost of production be reduced to a minimum.

The purpose for which direct-current dynamos are frequently designed is to light a number of incandescent lamps joined up in parallel circuit. It is necessary to maintain a constant potential difference at the terminals of these lamps, and consequently the machine employed should be shunt-wound, with a very low armature resistance; or, if the number of lamps is likely to be subject to considerable variation, the machine may be compound-wound. The modified rules of the Board of Trade which allow a maximum pressure of practically 480 volts for direct-current working has effected or permitted a revolution in the equipment of public supply stations. If it is not already clear to the student, he will learn from subsequent chapters that in extensive distribution systems, even a moderate increase in voltage results in an appreciable economy in the cost of mains, owing to the reduced quantity of copper required to transmit a given amount of energy. We are not far from the actual truth when we estimate the prime cost of the distribution network as being about equal to the rest of the plant. Engineers, therefore, usually arrange to develop a pressure of somewhere between 440 and 480 volts and employ the three-wire system of distribution (explained in Chapter XVII.), so that the pressure at the lamp terminals varies normally from 220 to 240 volts, while

for electric motors the full pressure of from 440 to 480 volts is applied.

For the important work of 'charging' secondary batteries, a simple shunt-wound machine is, for reasons explained in Chapter XIV., the most suitable, and this method of winding is, as we have said, also largely employed for lighting and power purposes.

Many dynamos are employed for the deposition of metals, electroplating, &c., and for this purpose they are in some cases required to furnish very heavy currents at an exceptionally low potential difference. They are frequently series-wound, and it is necessary that the internal resistance should be extremely low, otherwise considerable power would be wasted by the passage of the current, which sometimes exceeds 1000 amperes. To obtain this low resistance a drum armature may be constructed with very massive bars for the active conductors, the field-magnet coils consisting of a few convolutions of massive copper band. The armature should, however, be provided with a 'lap' winding, by means of which the number of armature paths is made large, and consequently the armature resistance and the section of conductor can be kept within reasonable limits. An electro-motive force of from six to eight volts is usually ample, and this, notwithstanding that there are but comparatively few active conductors round the armature, can be obtained without the necessity for driving at a high speed. But it is not an easy matter to secure these massive bars, and consequently many machines are made with a number of fairly thick wires joined in parallel to form one conductor. In order to reduce as far as possible the loss of energy at the commutator it is essential that the brushes should be large, and the amount of contact surface considerable. Machines of such exceptionally low E.M.F. are, however, falling into disuse, the more recent practice being to join the depositing tanks in series, and to employ a machine giving a correspondingly higher E.M.F.

A large machine, somewhat similar in appearance to that depicted in fig. 212, has been constructed for electro-deposition work; it develops the comparatively high E.M.F. of 50 volts, and can yield 1000 amperes at a speed of 350 revolutions.

For supplying current to a number of pieces of apparatus joined up in series, whether arc-lamps, low-resistance incandescent lamps, or motors, it is necessary to maintain a constant current under all conditions. The two open-coil machines described in this chapter are suitable for this class of work, but it is a system which is fast becoming obsolete, mainly on account of the low efficiency of such machines.

CHAPTER XII

MOTORS AND THEIR APPLICATIONS

WE must now give some attention to the important class of dynamo-electric machines employed for the purpose of converting, at any desired point, energy supplied to the machine, in the form of electricity, into energy in the form of mechanical motion.

In its widest sense this conversion rests upon the fact that whenever any of the lines of force forming part of two separately generated magnetic fields traverse a common space, there is a decided action between the two sets of lines, the tendency being to so alter their paths that as many lines as possible shall coincide in direction. By bearing in mind this simple general rule little difficulty should be experienced in predicting the results which will follow, even in complicated cases. This mutual action takes place independently of the means by which the fields are generated, whether by currents in two wires (straight or coiled, with or without cores), or by permanent magnets; or, the one field by a current in a wire and the other by a magnet. In the effort to make the coincidence a maximum, both fields are distorted from the configuration which they would independently have retained, and this configuration is again assumed immediately they are removed from each other's influence. Consequently, when the lines of force pertaining to two fields approach each other the result of their mutual action is an effort to impart such a motion to the material substances (whether a steel bar or a conducting wire) employed in generating the fields as to make them take up positions in which the lines of force due to both fields coincide to the greatest possible extent. The stronger the fields, the greater is the force thus acting, and, if sufficiently strong, mechanical motion is imparted to that body which moves the more freely.

For instance, suppose one field to be a simple one developed between the two pole-pieces of a powerful field-magnet such as has been described; and the other field to be generated by a current in a circular loop of wire. If the loop is placed vertically with its edges towards the pole-pieces—that is, with its plane parallel to the lines of force of the field-magnet—then the lines of its own field will be projected at right angles to those of the other, and the field-magnet being too massive to move, the loop will, if freely suspended, immediately turn round through 90°, when the lines of force due to the field-magnet thread through it in the same direction as its own lines. If free to move in any direction, its ultimate position of rest will be in the densest portion of the field, where the number of lines passing through it, and coinciding in direction with its own lines, is a maximum. If the current through the loop is then reversed in direction it will be in a position of unstable equilibrium, and the least movement will cause it to turn completely round until the lines of both fields again coincide.

We have thus a means of imparting mechanical motion to a material substance, in this case a loop of wire; and a continual rotatory motion can be maintained by reversing the current in the loop at the right moment, viz. just when its momentum has carried it a little beyond the point which, in the absence of this reversal, would be its position of rest. It remains to be seen how the principle is practically applied, on a scale such that the force with which the movable body is urged into a new position may amount to many horse-power.

Referring to the simple case of a closed-coil armature with a two-part commutator, as illustrated in fig. 183, it will be observed that if a current is sent through the two coils in parallel while in the position shown, no movement of the armature can result when the direction of the current is such that the lines of force due to it coincide in direction with those of the fixed field. This is the position of rest for the armature, and if the current in it is then reversed, it will make half a revolution until the same coincidence again exists. Now the current can be supplied to the armature from some external source: for example, a dynamo machine may be connected to brushes pressing on the commutator

segments, and so placed that each segment slides into contact with a fresh brush directly the position of rest as defined above is arrived at. By this means, although the current from the dynamo machine will remain unchanged in direction, the current in the armature coils will be reversed, and a continuous rotation kept up. With only two coils, the armature might come to rest suddenly at a dead point, and would not start again from such a position; or its direction of rotation might be reversed; but the number of coils can be increased with advantage until we have, practically, an armature similar to those used in generators. On a current being sent through such an armature, each coil strives to set itself with its plane at right angles to the field, in which position the coincidence of the two sets of lines is at a maximum. Immediately the coil arrives at this point, the current in it is reversed, causing it to exert a similar force in the same circular direction, during another half-revolution; and while any one or more coils are at or near the point of reversal where they exert but little turning effort, the other coils being in more active positions effectively keep the armature rotating.

The armature may be of the ring or drum type, it may be bi-polar or multipolar, and it fortunately happens that most of the principles underlying the design and construction of a good generating dynamo hold equally well for a motor. The fixed field is usually supplied by powerful electro-magnets, as in the case of generators, these being excited by a current from the same source as that which supplies the armature. Many of the troubles which in dynamos are avoided or reduced by the employment of a fixed field sufficiently strong to overpower that developed by the armature, are also inherent in a motor, and may be avoided by the same device. But in a motor the question of weight is frequently of considerable importance. For instance, the machine may be employed for the purpose of propelling a vehicle, and in such cases the weight of the motor is added to that of the vehicle, and involves a proportionally increased expenditure of power in moving it. Since the field-magnets are the heaviest part of the machine, the greatest reduction in the gross weight can be effected most readily by reducing the mass of iron in the field-magnets, and for this reason some motors have less massive magnet-cores than

purely theoretical considerations might dictate. Again, in constructing a motor, even more care must be exercised than with a dynamo, in rendering the armature able to resist sudden heavy stresses without risk of damage, the reason for which will be more apparent presently.

We have already learned that when a conductor moves through a magnetic field in such a manner that it cuts the lines of force transversely, an E.M.F. is induced in the wire, this E.M.F. depending upon the density of the field and the velocity of the wire; the cause which sets the wire in motion being quite immaterial. And if an independent current is already flowing in the wire, the electro-motive force induced by the motion will tend either to increase or decrease this current, according to its direction. Now when a wire, free to move, is placed in a certain position in a magnetic field, and a current is sent through it, it quickly moves to a new position. But in the very act of moving across the field, the wire cuts the lines of force, and an electro-motive force is consequently induced in it. The fact that the lines of force so cut by the wire form part of the same field which gave rise to the motion, as is the case with the armature conductors in a motor, makes no difference in the result. The direction in which this electro-motive force, due to the movement of the wire, will be impressed, may readily be predicted for every conceivable case, because, as such reactions always tend to stop the motion of the moving body, and as any reduction in the current must necessarily reduce the force with which the wire is moved (by the mutual action between the fields), the induced E.M.F. must always oppose and reduce the current which is flowing. The electro-motive force so generated by the movement of a motor armature is known as the 'back electro-motive force' or the 'counter electro-motive force'; it is always opposite in direction and necessarily less in value than that applied to the terminals of the motor, which latter may be referred to as the 'impressed electro-motive force.'

In consequence of this counter electro-motive force, the current which a given external source of E.M.F. can send through a motor is not determined solely by the resistance, but varies with the speed at which the wire of the movable part of the machine is

at the moment cutting the lines of force of the field. When the revolving part—that is to say, the armature—is forcibly restrained from moving, no counter E.M.F. is set up, and the current is then at its maximum, being simply the quotient of the E.M.F. divided by the resistance. But when the armature is allowed to move, a gradually increasing counter E.M.F. is set up, and the current falls correspondingly in value. The higher the speed at which the armature rotates, the greater does the counter E.M.F. become, and consequently the feebler is the strength of the current. This may be observed experimentally by placing an ammeter in circuit with a dynamo or battery and a motor, and then varying the speed of the latter.

Now, any one of the dynamos hitherto described can be used as a motor. For instance, we may take a direct-current series-wound machine, and, by simply passing a current through it from a battery of secondary cells, can cause the armature to rotate rapidly. The force with which the armature moves, or the twisting force, or 'torque' which it experiences, depends upon the strength of the fields produced by it and by the field-magnet, and these in their turn depend upon the strength of the current.

The internal resistance of a secondary battery is very low, and if that of the machine is also low, an enormous current will pass while the armature is at rest; sufficiently strong, if maintained for any length of time, to damage it. But immediately the armature begins to move, this enormous current falls, until presently the speed of rotation and the counter electro-motive force may become so high that only a small current can flow, the torque being, of course, also considerably reduced. This variation is extremely convenient in some cases: for example, when a motor is employed to propel a tram-car it is required to exert very much greater power to start the car from rest, than to keep it in motion after it has been started. It is just when the car and the armature of the machine are at rest that an enormous current can be sent through the machine, and a correspondingly great power exerted on the shaft; while the current falls to a safe value when a start has been effected, and before any damage can be done to the machine by over-heating. The necessity for its being able to assist such sudden heavy stresses as that caused by the

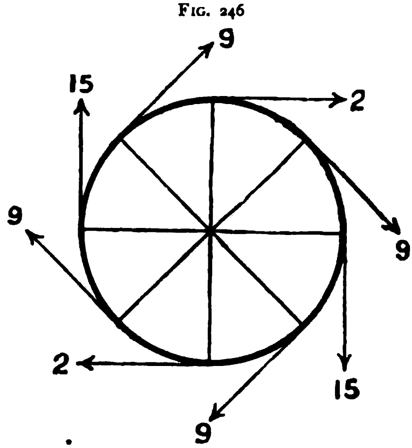
effort to start with a heavy load requires exceptional care to be exercised in the mechanical construction of a motor armature, especially with a view to prevent the stripping of the conductors from the core.

The term 'torque' is frequently employed, and merits some further consideration, especially in its application to the case of a motor armature. It is, as has been indicated, the twisting-force which an armature or other similar arrangement experiences, and represents the effort made to cause rotation. This effort is made up of two components, first the pull which may be measured in pounds, applied at a point at a given distance from the centre of the shaft; secondly, the length of the arm at which this pull acts—that is, the distance measured in feet of the point at which the pull is applied, from the centre of the shaft. Suppose, for example, the radius of the armature were 6 inches and a pull of 20 pounds were applied at a point on its circumference in a direction at right angles to the radius, then the torque, or the effort thus made to rotate the armature, would be $20 \times 0{\cdot}5 = 10$ pound-feet. If the diameter of the armature were doubled, thus giving an arm or radius of 1 foot, the torque would also be doubled, being $20 \times 1 = 20$ pound-feet, and so on. In the case of an actual armature the pull is exerted not at a single point on the circumference, but at a number of equidistant points—at every armature conductor, in fact—and as the distance of every conductor from the centre of rotation is nearly, if not quite, the same, the resulting torque may be found by multiplying together the sum of the pulls on all the conductors by the radius, or their common distance from the centre of rotation. For example, if the number of active conductors round the circumference were 100, the pull on each 15 pounds and the diameter of the armature 18 inches (radius 9 inches $= 0{\cdot}75$ foot), the torque would be $100 \times 15 \times 0{\cdot}75 = 1125$ pound-feet.

The pull or drag experienced by an armature conductor is not, however, the same at all points of its circular path through the field, as was assumed in this case. In the first place, the field varies in strength at different parts of the path through which the conductor sweeps; and secondly, the current in every section of the armature falls to zero for a moment while its particular commutator bars are passing under a brush, so that

during that moment the pull on the conductors of that particular section is *nil*. The value of the pull on the conductors round a motor armature varies, in fact, in much the same way that the activity of the conductors round the surface of a dynamo armature changes, being at a minimum along the diameter of commutation, and rising to a maximum at right angles thereto. It will also be evident that the counter electro-motive force developed by every individual conductor rises and falls in value with the drag upon it, being equal at any moment to that electro-motive force which it would develop if the armature were driven mechanically as a generator and lines of force were cut effectively at the same rate.

FIG. 246



If, however, the strength of the field and the strength of the current in the armature remain constant, the sum of the separate forces acting on all the armature conductors remains constant in value, because as each conductor passes from the position of greatest activity its place is taken by another, and so on. We can therefore make such a calculation as that just given by first calculating the total force or pull acting upon all the conductors at any moment, and then dividing by the number of conductors in order to obtain the average force or pull on one conductor.

In fig. 246 we have represented a state of affairs more nearly approaching to that which obtains in an actual armature, where the diameter of commutation may be taken as being a few degrees from the vertical, and for simplicity only eight active conductors are indicated. The pull on each conductor acts at right angles to the diameter of the armature passing through that point, because

the lines of force nearly all enter at right angles to the surface of the armature core, and every conductor is urged across the field at right angles to the lines of force. Even were this not so, the reduced resultant force acting at right angles to the diameter would be the force which we should have to consider, since it would be the only part of the total force acting effectively to rotate the armature. The figures placed against each arrow-head represent the pull in pounds experienced by each armature conductor, and each conductor is at the moment impressing upon the shaft a torque or twisting force equal to its particular pull multiplied by the length of the arm at which it acts—that is to say, its distance from the centre of rotation. Let this distance or radius r equal 6 inches; then, since each pull acts in the same direction round the coils, the total torque is the sum of these separate values, or

$$\begin{aligned} & 2r + 9r + 15r + 9r + 2r + 9r + 15r + 9r \\ &= (2 + 9 + 15 + 9 + 2 + 9 + 15 + 9)r \\ &= 70r = 70 \times 0{\cdot}5 = 35 \text{ pound-feet.} \end{aligned}$$

This proves the statement previously made, that the torque may in any case be estimated by multiplying the sum of the pulls on each conductor in pounds by the radius of the armature measured in feet or a fraction of a foot.

As a simple practical example we may assume the case of a motor armature 12 inches in diameter (6 inches radius) with 100 active conductors, and giving on the shaft 12 horse-power when the speed is 500 revolutions per minute. The whole of this power appearing on the armature shaft is first transmitted by the conductors through the core to the shaft, and from the figures given we will discover first the torque, and secondly the average pull in pounds on the conductors. One horse-power is equivalent to a rate of working equal to 33,000 foot-pounds per minute, and consequently we have in this case a rate of working equal to $12 \times 33{,}000$, or 396,000 foot-pounds per minute.

The whole of this power being impressed upon the armature conductors, we can, if we know the distance in feet through which they travel in one minute, divide by this distance, and obtain the force in pounds exerted at any moment on the whole of the

conductors. Any one conductor in every revolution travels round a path equal to the circumference of the armature ($2\pi r = 2\pi \times 0{\cdot}5 = 3{\cdot}14$ feet) and passes therefore through $500 \times 3{\cdot}14 = 1570$ feet in one minute when the armature makes 500 revolutions per minute. Consequently the actual pull exerted upon the armature conductors is $\frac{396{,}000}{1570} = 252$ pounds. From this we see that the torque must be $252 \times 0{\cdot}5 = 126$ pound-feet, and the average pull per conductor $2{\cdot}52$ pounds.

The pull on any one conductor when at the most active part of its journey amounts to a much higher value than this average pull; and in a powerful machine the value becomes exceedingly high, especially when, as at starting, the back electro-motive force is *nil* and the current through the armature becomes abnormally high. These considerations emphasise the necessity for an effective mechanical connection between the conductors and the armature core, which can be best secured by embedding the conductors in slots in the core.

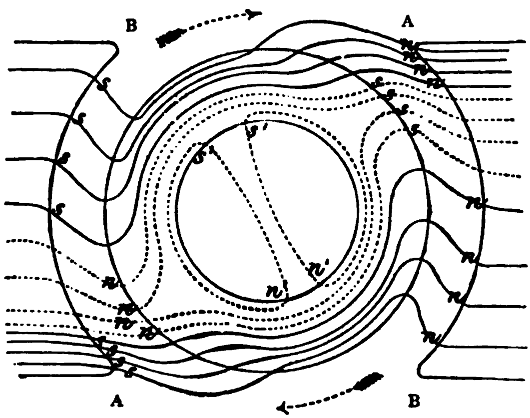
Supposing the field to be the same in both cases, the direction of the current in the armature of a machine when used as a motor must be the reverse to its direction when used as a generator, if the direction of rotation is desired to be the same in each case; indeed, we have just seen that the counter E.M.F. generated is opposite to that which produces the driving current.

If, therefore, the direction of the driving current applied to the terminals of a series machine is the same as that which would be developed by the machine itself when driven as a dynamo, and if the direction of rotation is to be the same for a motor as for a dynamo, the connections either of the armature or of the field-magnets must be reversed. If, however, a rotation in the opposite direction is desired when running as a motor, the connections should remain unaltered, and the brushes turned round to suit the reversed rotation. A shunt dynamo, on the other hand, will, without any alteration, turn in the same direction if an E.M.F. opposite to that developed by it as a generator is applied to its terminals, for the current through the armature is then in the reverse direction, while that through the field-magnet coils is the same as before. This will be apparent

on inspection of the diagrams of the shunt dynamo connections given in figs. 197 and 198; when employed as a generator the field-magnet coils form a shunt to the external circuit, but when used as a motor these coils act as a shunt to the armature.

The distortion of the field observed when a machine is used as a generator also occurs when it is employed as a motor, because, when the brushes are at zero, the lines of force of the armature field are at right angles to those of the field-magnets. But the direction of the current, and therefore of the lines of force, being reversed in the case of a motor armature, the direction of the resultant field is also different. The amount of the distortion

FIG. 247



depends, obviously, upon the relative strengths of the two fields. It is very slight when the field-magnets sufficiently overpower the armature, but in all cases the direction of the resultant field is such that the brushes must be shifted *backward* to place them on a diameter at right angles to the lines of force, and so to avoid sparking.

The distortion of the field of a motor is illustrated in fig. 247, which should be compared with the corresponding figure (193) for a generator. The density of the lines of force is greater at the horns A A which the armature is approaching, and, as a consequence, any irregular distribution of iron in the armature core

causes stronger eddy currents, and develops more heat at these places than, as in the case of a dynamo, at the horns B B from which the armature is receding. With an ordinary armature having a smooth core this heating is hardly appreciable, and in all cases it is influenced to a certain extent by the fact that a current of cold air is drawn in at A A and ejected somewhat warmer at B B. In the case of a motor, therefore, this air current tends to reduce, and in the case of a generator to increase, the difference of temperature between the two horns of each pole-piece.

The current through the armature of a motor frequently varies considerably, and this may cause a shifting of the resultant field, and therefore also necessitate an alteration in the position of the brushes; but in all cases a reduction in the angle of lead, and immunity from sparking due to a variation of the armature current, may be obtained by employing a very powerful field relatively to that produced by the armature. In many motors now in use the load can be varied considerably without any readjustment of the brushes; and an effort is always made to reduce the number of convolutions per coil in the armature, thus minimising one of the causes of sparking.

The electrical power may be supplied to a motor either at a constant pressure, or with a constant current; in the former case regulation is comparatively easy, while in the latter greater economy in the distribution of power can sometimes be effected. Supposing a constant potential to be maintained at the terminals of a shunt-wound motor; the current through the field-magnet coils will always be the same, and therefore the strength of the field remains constant, but the current through the armature depends upon the speed of rotation, being, in fact, determined by the excess of the applied electro-motive force over the counter electro-motive force. Supposing the machine to be employed in driving a tram-car; then, for example, when the car commences to mount an incline, the armature shaft is called upon to perform additional work, which tends to reduce the speed of rotation. This reduction of speed, by reducing the counter electro-motive force, immediately allows a stronger current to pass through the armature, and affords the necessary additional torque to perform the extra work. On the other hand, should the car be allowed to

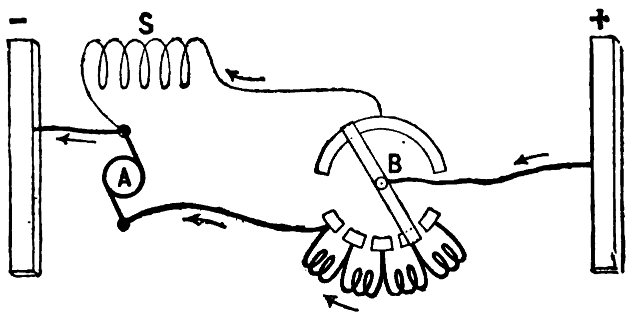
attain a high speed in descending an incline, the counter E.M.F. would reach a high value, so high in fact that very little current would pass through the armature, whence very little electrical power would be expended. The demand upon the source of the electrical power is thus to a certain extent automatically regulated in a very simple manner according to the requirements, and this effect of the counter electro-motive force obtains whatever the purpose may be for which the machine is employed.

If the armature resistance is extremely low and that of the shunt-coils high, and if the field-magnet develops a much greater field than the armature, the variation of lead will be but slight, and, further, the machine will to a great extent be self-regulating as regards speed.

Many motors now constructed satisfy these conditions sufficiently to render any other aids to regulation superfluous. But some precautions are needed in joining such machines in circuit, especially if, as is usually the case, any load is applied to the shaft before the armature has approached its normal speed. Even though the potential difference between the mains to which the machine is to be connected were no more than 100 volts, this would give rise to an enormous current through the armature, before it had time to get up speed and develop the counter E.M.F. which would be competent to reduce the current to a safe value. The armature while at rest would in fact simply short-circuit the mains and the field-magnet coils, and the latter fact would, by preventing the rapid establishment of a powerful field, tend to retard the armature getting up speed. In any case the field-magnets, if massive, take an appreciable time in becoming fully magnetised, and it is advisable to start such a shunt-wound machine by first joining the field-magnet coils directly across the mains, then joining the armature in series with a considerable resistance across the mains, gradually cutting out this resistance as the armature rises in speed. Such an arrangement is indicated in fig. 248, where A represents the armature, S the field-magnet coils, and B a switch with four resistance coils, the positive main being shown on the right and the negative on the left. One end of the metallic switch bar or lever, which is connected to the positive main, passes over and makes good contact with a curved brass strip which is joined

to one end of the field-magnet coils; the other end of the switch bar passes over five metal studs, to which the resistance coils are connected as shown. In order to disconnect the motor and stop it, the switch bar should be turned left-handedly through about 60° from the position shown, when it would lie clear of the studs and also of the curved bar. To start the motor the bar must be turned right-handedly from this position of disconnection, when its upper end will first make contact with the curved strip, thus allowing the current to pass through the coils S and excite the field-magnet. It will be observed that this end of the bar will make contact with the curved strip and complete the field-magnet circuit before its other end makes contact with the

FIG. 248



extreme right-hand stud; but by further turning the switch bar in the same direction, the lower end makes contact with this stud and completes the armature circuit, all the resistance coils being then in series with the armature. The resistance coils have such a value that even were the armature not to start, the current would be insufficient to damage it, and the coils themselves should be made of bare wire sufficiently thick to carry the maximum current. When a current is thus started through the armature, it should at once commence to rotate and develop a counter E.M.F., and the switch bar can then be moved on to the next stud (the position indicated in the diagram), when only three coils are in series with the armature, which under the influence of the more powerful current rotates yet faster, and the switch bar can be finally

moved up to the extreme left-hand stop, when all the resistance will be cut out of circuit and the armature joined direct across the mains.

In some cases where exceptionally good regulation is desired, and where the armature resistance cannot well be made sufficiently low and the field sufficiently powerful to secure it, other devices may be employed. We have seen that when an additional load is thrown on the motor, the resulting reduction in speed immediately allows the passage of a stronger current through the armature ; but if the speed is to be kept constant, the counter electro motive force will also be constant and then the current through the armature can hardly vary at all, so that the two conditions are opposed to each other. But by reducing the strength of the field developed by the field-magnets, the counter E.M.F. can also be reduced, and therefore a stronger current can be passed through the armature when rotating at a given speed. It is necessary, then, in order to keep the speed constant, to devise some means of reducing the strength of the field when the load is increased and the current in the armature rises. One way of accomplishing this automatically is to place a few turns of thick wire round the limbs of the field-magnet, in series with the armature, but wound in such a manner as to magnetically oppose the shunt-coils instead of assisting them as in the case of a compound-wound generator. The effect of these series-turns in weakening the field becomes greatest when the armature current is strongest and *vice versa*; but it should be observed that since the strongest current which can pass through the armature (and therefore also through the series-winding) does so when it is at rest, the armature may start in either direction, as determined by the shunt-coil field or the field produced by the heavy current in the series-windings. To avoid any uncertainty, it is usual to lead the ends of the two windings and of the armature separately to the starting switch and to reverse the current through the series-windings, so that both shunt- and series-coils act together in developing a strong field in the right direction at the moment of starting, the series-turns being joined up in the normal manner when the speed rises above a certain value. The series-turns, being few in number, aid the shunt-coil but little when in series with it, because they are then

carrying a small current; and practically the same result may be obtained by simply short-circuiting the series-coils until the machine has been properly started.

The field of a shunt motor may also be weakened by inserting resistance coils as required, either by hand or automatically, or by altering the ampere-turns of the field-magnet coil in any other manner. It appears at first sight somewhat paradoxical that the speed of a motor can be increased by reducing the strength of the field, but the reduction of the counter electro-motive force allowing a more powerful current to be urged through the armature, as mentioned above, satisfactorily explains the matter.

In order to obtain the best results with a shunt-wound motor, the machine must necessarily be heavy and expensive in construction, and hence we find that such motors are generally used where they can be permanently fixed in position, and where approximate regularity of speed with varying loads must be secured at any cost, as, for example, in the driving of some classes of machinery. They have been tried and abandoned for traction work, as it was found that, in addition to the two disadvantages mentioned, it was impossible to avoid the armatures being burned up occasionally. This is due to the circumstance that electrical contact between the car and the feeding wire or wires (and sometimes the earth) must necessarily be made by sliding connections, and it is then impossible to avoid an occasional momentary disconnection of the circuit; when this happens the armature is liable to slow down or stop, and the field-magnets to become demagnetised; and the heavy current which can then be urged through the armature before the field-magnets can again be fully magnetised and the armature get up speed will probably be strong enough to burn up the armature. As will be seen presently, series motors fed at a constant potential are now usually employed for traction work.

The case for a series motor fed with a constant current may now be considered. Since the field-magnet and armature are in series with each other, the current in the one is always (unless specially arranged for otherwise) the same as that in the other; and this current is kept constant in value, being usually about 10 amperes. Consequently the torque, or the effort made by the armature to rotate, is always the same, no matter what the load

may be, because, as we have seen, this torque depends upon the strength of the field and the armature current, which in this case do not vary. The turning effort being constant, the speed therefore depends solely upon the load.

If the load is decreased, the speed increases, and so gives rise to a higher counter E.M.F., but the generator responds to this, and by developing a correspondingly higher E.M.F. maintains the current constant. Consequently the speed of the machine increases enormously when the load is lightened to a great extent, and it is then that unless care is taken considerable damage may be done.

On the other hand, when the load is increased the speed falls, and if the load is increased beyond a certain value, the armature will be pulled up. It will be seen that in the case of a constant current series-wound motor the power given out varies directly with the speed, and if it be desired to reduce the speed, this may best be effected by diminishing the strength of the field, the armature current being kept constant. The resulting reduction in the counter E.M.F. simply causes the generator supplying the current to develop a lower E.M.F., because a lower pressure at the terminals of the motor becomes sufficient to urge the proper current through it. The alteration in the strength of the field is conveniently effected by shunting the field-magnet coils with a variable resistance, or by cutting out some of the convolutions of those coils, and in some instances this has been successfully performed automatically by means of a centrifugal governor driven from the armature shaft.

Constant current motors are as a rule only used on arc-light circuits supplied with current by open-coil machines—that is to say, they are only used when the circumstances are such that no other type can be employed. In addition to the difficulty of securing satisfactory regulation the impressed E.M.F. or the potential difference at the terminals of the machine is always considerable, and it becomes dangerously high in the case of a large motor, because the current being constant an increase of power can only be obtained by increasing the impressed E.M.F.

Series-wound motors can be employed with much more satisfactory results on a constant potential circuit, and this arrangement

is adopted on nearly all of the more successful electric railway and tramway lines, and indeed in almost every case where the motors have widely varying loads and where they have to be frequently started and stopped or even reversed in direction. Generally speaking, for such work we do not require the motor either to run at a constant speed, to exert a constant torque, or to develop constant power, and it fortunately happens that when the maximum torque is demanded, the speed can then conveniently be lowest.

If a series motor be connected between two mains kept at a constant potential difference, the current passing through the motor, and therefore the torque, will depend very largely upon the back E.M.F., which in turn depends upon the speed at which the armature is rotating. Now the speed is governed chiefly by the load, so that when the load is light, the armature having but little resistance opposed to it, will rotate rapidly and generate a high back E.M.F., thus reducing the current until the torque is that required by the particular load. It should be noted that the torque is reduced in two ways, first by a fall in the armature current, and secondly by an equal fall in the field-magnet current, giving a corresponding reduction in the strength of the field. Conversely, when the load is increased the speed of rotation falls and with it also the back E.M.F., thus allowing a stronger current to flow through the armature and field-magnet coils, giving the necessary increase in torque to deal with the heavier load, and also tending to again increase the speed, although perhaps the latter may not attain such a high value as it does when the load is light.

As a series motor offers but little resistance, and as the pressure adopted for traction work is usually about 500 volts, the current passing through the machine when at rest would be sufficiently strong to burn it up, and consequently a set of resistance coils is generally thrown in series with the motor until it has had time to start and develop a sufficient back E.M.F. to bring the current down to a safe value. This resistance may be gradually reduced by a suitable switching arrangement, and cut out entirely when the motor has got up speed and the full power is required. This arrangement also admits of speed regulation to a considerable extent. It is evident, however, that a considerable

amount of power must be wasted by the frequent employment of such resistance coils: such waste can be reduced by coupling two motors to each car, and when the maximum power is required, as at starting, joining the motors in series with each other. The current necessary at starting is thus reduced to about one half the value it would have if only one motor were used, and the power wasted in the resistances is correspondingly reduced. When the speed has risen sufficiently the motors are joined in parallel with each other, but in series with resistance coils, which latter are then cut out as the maximum speed is attained. A description of the apparatus for effecting these and other similar changes is given in a later page.

Only a portion of the power given electrically to a motor is converted usefully into mechanical power, a part being spent in heating the armature, field-magnet coils, &c. When the armature is *held* at rest the whole of the electrical power absorbed by the motor is thus converted into heat, and the efficiency of the machine —that is, the ratio of the useful power obtained on the shaft to the total power supplied—is then at its lowest value, viz. nought. When the armature is allowed to move, the useful performance of work begins, and as the current also then falls in strength, the power wasted in heating decreases. The higher the speed of rotation, the higher becomes the counter E.M.F. and the less becomes the power wasted as heat in the conductors. The ratio of the mechanical power developed by the motor to the whole power supplied, is proportional to the ratio of the counter E.M.F. to the E.M.F. applied at the terminals of the machine. The torque, or the effort made by the armature of the motor to rotate, is greatest when the load is sufficiently great to prevent the armature turning, and when, therefore, the motor is doing no useful work at all. Now when a motor is running at a high speed and with a comparatively feeble current through the armature, it performs very little work indeed during one revolution, although, the number of revolutions being great, a considerable amount of work may be performed during a given interval of time, say one minute. On the other hand, when the speed is very low the amount of work per revolution is comparatively great, but the small number of revolutions per minute prevents the quantity of

work reaching during that interval a very high value. By considering these two extreme cases, it might be supposed that there is a certain intermediate speed of rotation at which the work performed by any given motor is a maximum. This is the case, and the speed of a motor at which it can perform the maximum amount of work per minute is that speed at which the counter electro-motive force becomes equal to half the electro-motive force applied at the terminals. This result is quite independent of the *efficiency* of the conversion, which, as we have seen, increases with the speed of rotation, and the efficiency of any motor when it is doing the maximum amount of work which it can do, is so low (about 50 per cent.), that in practice motors are not worked under such conditions for any length of time.

In most cases the difficulty of obtaining a machine of reasonable efficiency at a low speed, without abnormal proportions and correspondingly heavy weight, renders it necessary to run at a high speed, and to effect the reduction required by suitable gearing. Thus, for example, the wheel of an ordinary tram-car travelling at seven miles per hour does not revolve at so high a speed as 80 revolutions per minute, but it would be impossible to construct a practical motor to run at this low rate. A machine running at say 720 revolutions might be employed, by introducing gearing which would reduce this speed to about one-tenth. The selection of suitable gearing is not, however, an easy matter, for it must be light, strong, and durable, and should produce neither noise nor vibration in working; and, while absorbing little power in friction, it must be capable of withstanding dust and dirt, or of being easily protected therefrom. Some very good devices, depending upon friction to transmit the power from a small wheel on the rapidly rotating armature shaft to a larger pulley on the axle, have been employed with fair success on lines where the gradients are slight; but where the power required to be transmitted is at times very heavy, this method is not to be relied on. By means of a pinion and spur-wheel, with or without an intermediate counter-shaft, very great power can be transmitted. The objections to this gearing are that it is unusually noisy, and that the teeth of the pinion on the armature shaft rapidly show signs of wear; but it is, nevertheless, the gearing most frequently adopted,

the objections to a great extent being overcome by making the pinion and spur-wheel of steel with accurately cut teeth of the most approved shape.

The necessary reduction in speed can also be obtained, and in a very satisfactory manner, by means of a screw and worm-wheel; a screw, driven by the motor shaft, gearing into the teeth of a worm-wheel on the axle of the car or on a counter-shaft. The only objection to this method is that in order to obtain perfectly satisfactory results the gearing must be extremely well made, and it is then expensive. Chain-gearing has also been employed; in this case an endless chain passes over a small toothed wheel on

FIG. 249

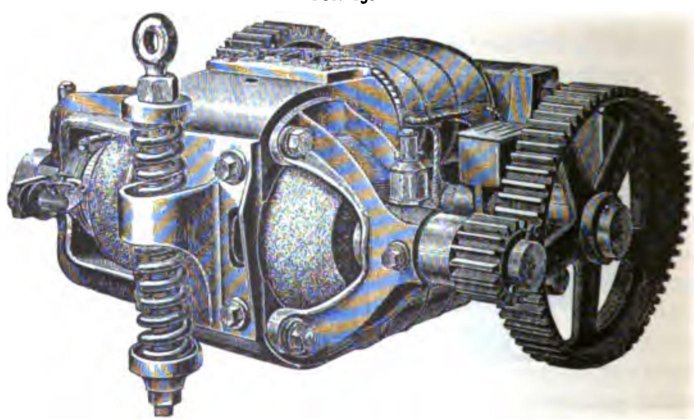
the motor shaft and a larger one on the axle, the teeth of the wheels fitting into the links of the chain. The chain is, however, liable to stretch, and then the teeth no longer fit accurately, and slipping is likely to take place.

In figs. 249 and 250 a good example of spur-gearing is illustrated. The motor is of an old type, intended for use on a tram-car, the field-magnet being of the single horseshoe type, and of wrought iron throughout. At the yoke end, the motor is swung from the axle of the car, this bearing being shown to the left of fig. 249, while at the other or armature end it is flexibly supported, being attached to the body of the car by means of the spring shown in fig. 250. Bronze brackets, fixed to the pole-cheeks,

support the armature bearings, and a pinion on the armature shaft, as indicated in fig. 250, gears with a spur-wheel carried on a counter-shaft, which passes between the limbs of the field-magnet. At the other end of the counter-shaft is the pinion visible in fig. 249, which gears into a spur-wheel keyed on to the axle of the car, the number of teeth being so proportioned that the speed of rotation of the axle is about one-twelfth of that of the armature.

The pinion on the armature shaft is sometimes made of hard vulcanised fibre or compressed leather. The wear is, of course, greatest at the teeth of this pinion, while the greatest power is

FIG. 250

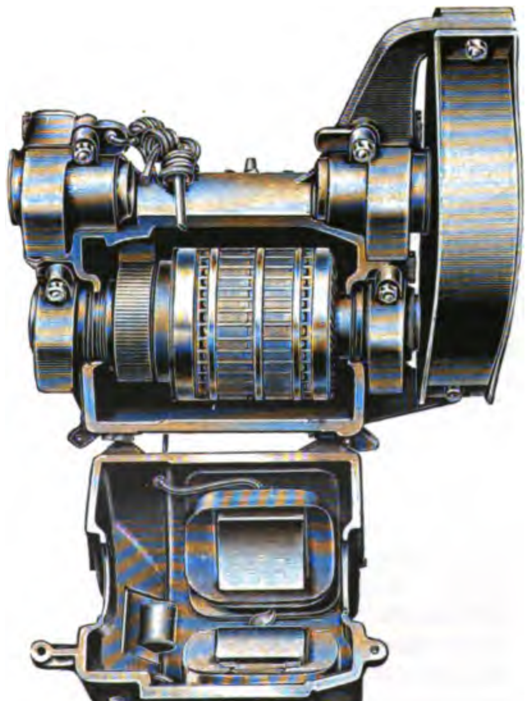


transmitted individually by the teeth at the other end of the train of wheels. The teeth are, however, strong enough to resist a *steady* pressure far greater than can be given by the machine; were the full power suddenly applied with a jerk, the strain would be enormously increased, but a most important function of the supporting spring is to prevent this jerk taking place, by yielding slightly when the pressure is suddenly applied. But the advantage gained in this way entails the disadvantage that the distance between the centres of the engaging wheels is liable to variation. Consequently, involute teeth are employed—that is to say, the form of the rubbing surfaces of the teeth is the involute of a circle, such teeth being

the only ones which are independent of an alteration in the distance between the centres of the wheels.

The motor referred to has done good service for street tramway work in America, but it has been considerably improved upon, and we may, perhaps, select for description as a typical

FIG. 251



tramway motor that made by the Westinghouse Company, and it will be interesting to note the advance which has been made. Some of the principal features in the design of the Westinghouse motor may be gathered from fig. 251. The machine is suspended by means of a rectangular cross-bar bolted to facings on the frame,

and each end of this bar is attached to the wagon by springs. The car-wheel axle passes through two bearings in the machine frame which are visible at the top of the figure. The motor has one reduction in speed, which is effected by means of a pinion on the armature shaft which gears into a spur-wheel on the car axle. The pinion and gear-wheel are 5 inches in width, the former being of forged steel, whilst the latter is of cast steel, and is made in two parts which are bolted together and keyed on to the car axle.

This gearing is entirely enclosed in a case of malleable iron made in two parts, so that the lower half may be removed without disturbing the upper half. A hand-hole with a spring cover affords facilities for the inspection and lubrication of the gear-wheels. The field system has four poles which project radially inwards, and when in position the yoke is almost octagonal in shape, with well-rounded corners; but the yoke is divided into two halves which are hinged together and can be opened out as shown in the figure, thus exposing the armature and the two lower field-magnet coils. The pole-cores are built up of annealed soft-steel stampings, which are firmly riveted together between wrought-iron end-plates. Each pole-core is fastened to the yoke by two studs, which are screwed into double nuts embedded in the pole-cores. The field coils are wound complete on formers, insulated, taped, and again thoroughly insulated, it being of special importance that these coils should be made capable of withstanding atmospheric changes. Each coil is supported by a brass plate resting on the pole-shoe, and is slipped on the pole-piece before the latter is fastened to the yoke. The vibration to which traction motors are subjected is very great, and to protect the field coils from the effect of this, flat steel springs are fixed between them and the frame. The armature is of the drum type, and the core-plates, which are slotted to receive the conductors, are built up on a spider keyed firmly to the shaft. In order to protect the teeth of the core-plates there is at each end of the core a pressed steel plate slotted to correspond with the core-slots, and the whole are clamped together between cast-iron end-plates. The armature coils are wound on a former, and effectively insulated before being placed in position. After the

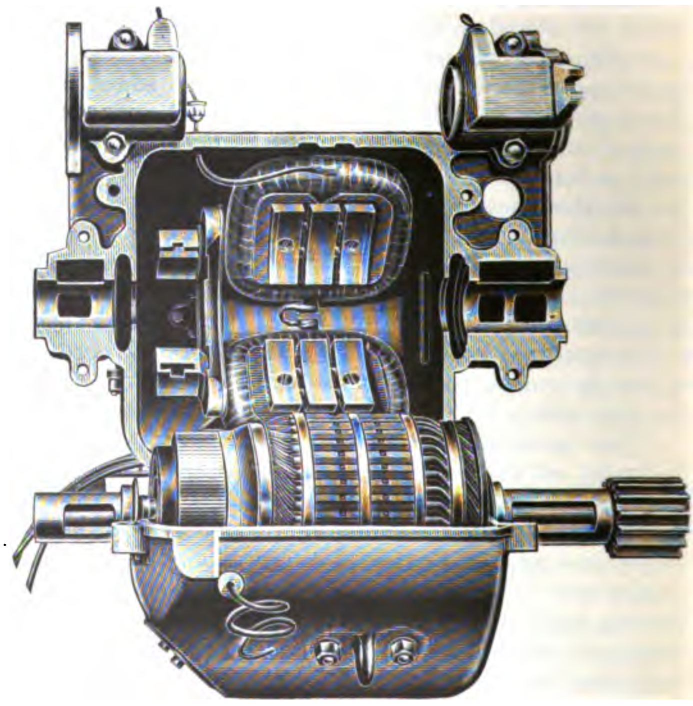
armature conductors have been wound, a number of turns of steel wire are wrapped tightly in grooves cut on the periphery of the core, in order to keep the conductors in position; the grooves are of such a depth that the wire bands are protected and prevented from being torn off in the event of the core coming into contact with the pole-pieces, a contingency which might arise from the wearing away of the bearings. The armature winding is of the series type, two sets of brushes only being employed, and these brushes are placed on the upper part of the commutator so as to be readily accessible from above. It will be observed that not only is the motor extremely compact, but it is admirably suited to very rough work under a tram-car even with a bad road. With a motor so completely encased to protect it from mechanical injury or from the entrance of water, it is evident that considerable sacrifices must be made as regards ventilation, but the risk of breakdown on account of overheating is reduced to a minimum by employing for the insulation only materials, such as mica, which are able to withstand a very high temperature; and, further, the quantity and disposition of the metal constituting the frame and field-magnets are such as to assist freely in the dissipation of heat by conduction and radiation. The weight of the motor complete with gear-wheel and gear-case is about 2760 lb.

These machines are in every case provided with series-wound field coils, and in the most approved practice two machines are employed on each tram-car, the regulation being effected by means of resistance coils, and by joining the two motors in parallel or in series as circumstances may require. The resistance coils must be so designed that, although they occupy little space, they are capable of dissipating a considerable amount of electrical energy without a dangerous rise in temperature. The most satisfactory method is found to be to make the conductor of strips of thin sheet-iron, closely wound and heavily insulated with mica, and placed in a cast-iron case fixed underneath the car.

A motor similar in many respects to the Westinghouse machine is constructed by the English Electric Manufacturing Company of Preston, in conjunction with Messrs. Dick, Kerr & Co. One of these motors is illustrated with the upper half of the frame raised, in fig. 252, and with the lower half let

down, in fig. 253. Its total weight is about one ton, and it is capable of developing from 25 to 50 horse-power. It is designed to maintain an output of 25 horse-power with a rise of temperature of not more than 75° C. in any of its parts after a continuous run of one hour, the temperature of the surrounding air not exceeding 25° C. The upper and lower halves

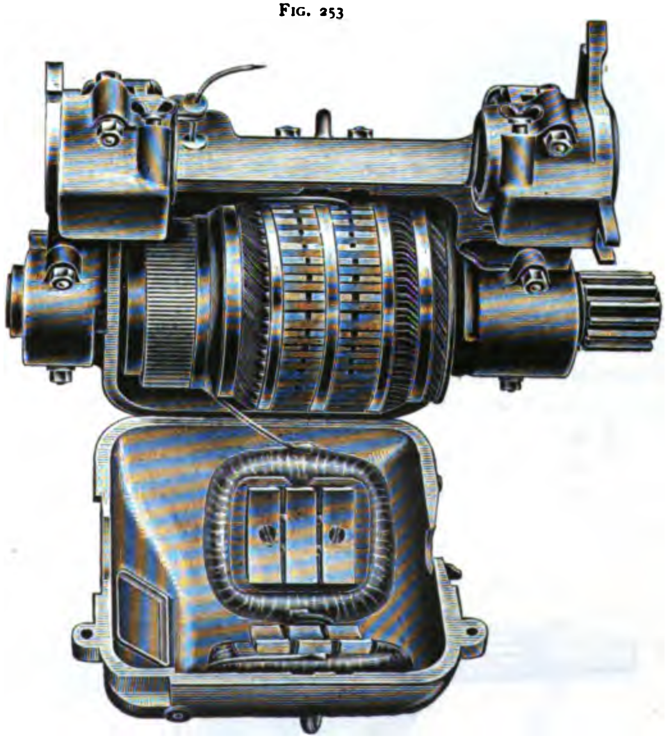
FIG. 252



of the field-magnets with their yokes and the covers for protecting the machine from dust and moisture are, it will be seen, freely hinged together and completely envelop the armature and its commutator, and by loosening the four bolts which secure the bearing caps, the armature can be withdrawn altogether. The yokes as well as the cores are constructed of iron of high

permeability, and are carefully fitted together in order that they may offer the minimum resistance to the lines of force. The bearing supports for the car-axle and for the armature shaft are cast on to the upper part of the frame, an opening (provided with a soft-iron lid) being made just over the commutator to

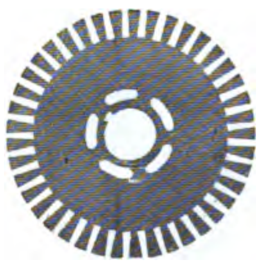
FIG. 253



facilitate access to the brushes for purposes of renewal, &c. It will be seen that the machine is of the four-pole type, the cores and pole-pieces being laminated and securely bolted to the cast-iron frame. The laminæ consist of mild-steel stampings riveted together, and each core is composed of three sets of stampings with air spaces between them for ventilating or cooling

purposes. The disposition of the field coils and the method of connecting them to the external circuit are clearly shown in the illustrations. These coils are machine-wound upon a frame or former of the same shape as the cores, and are insulated with asbestos and cotton. Each coil, after it has been wound and finished off to shape, is immersed in a bath of insulating compound which, entering the interstices between the convolutions, fills it up solid. After having been thoroughly dried it is served with a thick protecting cover composed of mica, paper and sheeting, and is then coated with strong braided tape impregnated with a waterproof material. A stiff bronze or copper frame is then forced into the coil to protect it from the core over which it is slipped, and to afford a means for securing it to the yoke-frame. This method of construction is of course an excellent mechanical arrangement, but the heat generated in the conductor cannot easily be dissipated.

FIG. 254



The armature core consists of a number of mild-steel stampings with a key-way, ventilating channels, and 41 teeth,

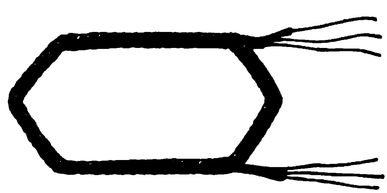
FIG. 255

as shown in fig. 254. These stampings are (see fig. 255) threaded on to a 3-inch hammered-steel shaft in which a key-way is cut throughout its length between the bearing surfaces, so that the key on being driven in shall keep the core and commutator securely in position and effectively prevent them from

slipping round. Spacing pieces are fixed at intervals between the core discs so as to afford facilities for ventilation, and a cast-iron head provided with a curved flange on its outer edge (shown to the right of the core) is driven on to the shaft to receive and protect the ends of the armature coils. A substantial iron washer is secured against the other end of the core by means of a steel hub and lock washer, clamping the whole securely together.

The commutator, shown to the left of the armature in figs. 252 and 253, is exceptionally large in diameter as compared with the armature itself. It consists of 123 bars of hard-drawn copper, 4 inches long and 1 inch deep. The commutator is mounted on a cast-iron hub which fits the armature shaft and is provided with two inwardly projecting V-shaped flanges. Moulded micanite insulating rings are fitted on to these flanges for securing the commutator bars and insulating them from the shaft. Mica insulation is, of course, used between the bars themselves, which have a narrow slot sawn into the armature end to receive the ends of the coil wires. The bars, with the mica strips, are fitted together and the ends turned up true and provided with the necessary V-shaped grooves before being fitted to the hub above mentioned, which is provided with suitable openings for ventilating purposes. It is interesting to notice that the insulation of the commutator is tested with an alternating current of 2000 volts between the bars and the hub, and of 500 volts between adjacent bars, before being finally secured in position on the shaft, which is effected by means of a screw and lock nuts.

FIG. 256



The armature coils are not placed in position until the commutator as well as the core has been fixed in position. The wire is covered with three layers of cotton thread, and the coils are machine-wound and accurately shaped, as in fig. 256, so as to be interchangeable. They are dried in an oven at a temperature of 250° F. in order to expel every trace of moisture, a process which is always necessary with cotton on account of the freedom with

which it absorbs water out of the air, &c. Immediately after the drying process the coils are immersed in an insulating compound to prevent the re-absorption of moisture and are then re-dried, the operation being repeated a number of times until an effectual coating has been applied sufficient to withstand any test which may legitimately be applied. Three coils are placed together and covered with mica, compressed cardboard and linen, and are then lapped over with two layers of thin wadding. The whole is then varnished and finally baked. The ends of the three coils are distinguished by coloured braidings, red, white, and blue respectively, in order to avoid any risk of mistake in connecting them to the various commutator bars. There are in all 41 of these triple coils, and as each has six ends, there are two wires to be connected to each of the 123 commutator bars. The object, of course, is to provide an armature which shall be equally balanced both electrically and mechanically. On referring to fig. 256 it will be seen that each coil has two straight sides, and one of these sides is placed at the bottom of each of the 41 core-slots, the other sides being placed in the upper portion of the slots. There are thus sections of two compound or six individual coils in each slot, and the machine being of the four-pole type the coils are just wide enough to embrace a quarter of the armature—that is to say, the coils are able to span just 10 teeth. When the coils are all in position they are securely bound with tinned steel wire (with a breaking strain of over 4 cwt.), as shown in fig. 252. These bindings are wound in grooves in the core, the teeth of which project slightly beyond the outer surface of the coils.

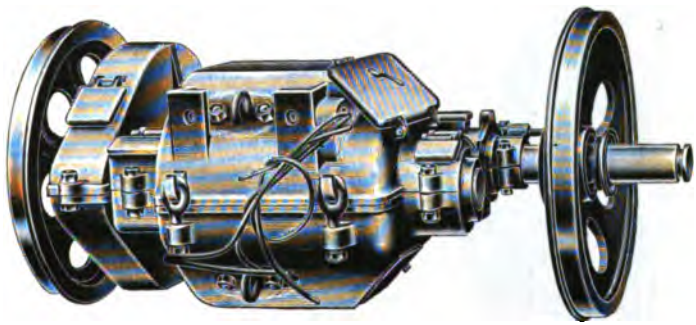
The power developed by the machine is communicated to the car by means of a hammered-steel pinion which has 14 teeth with a face of $4\frac{5}{8}$ inches, and gears into a toothed wheel on the driving axle.

The brushes, as in the case of nearly if not quite all modern motors, are of carbon. Each holder carries two mechanically independent brushes, which are placed at an angle of 45° on either side of the vertical plane on the upper half of the commutator, so as to be readily accessible from without. The brushes are adjustable lengthwise along the commutator, and are, of course, so constructed that they may be advanced to take

up the wear either of the commutator bars or of the brushes themselves.

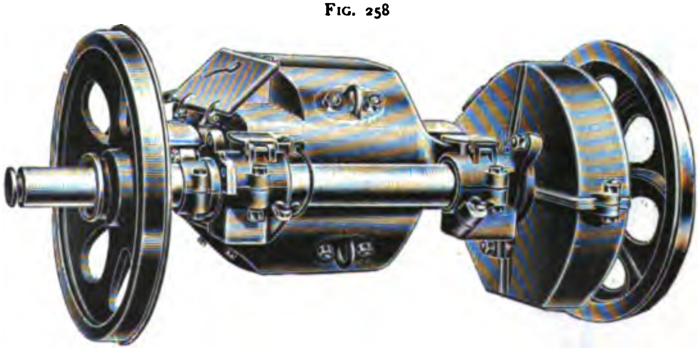
The armature bearings are of bronze and the axle bearings of white metal, each bearing having a cap or cover which is provided

FIG. 257



with a well capable of holding about a pint of oil. The oil is fed through wool wicks, provision being made for the excess oil to return to the wells. In the event of the oil failing, emergency lubricators are provided in the form of grease-boxes placed above

FIG. 258



them, the heat developed as a consequence of the absence of lubricating oil being relied upon to liquefy the grease and cause it to flow down upon the bearings.

Two motors are provided for each car, the front view of the

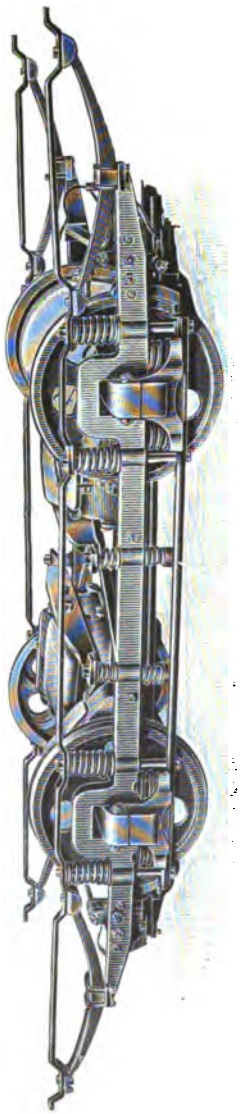


FIG. 259

motor mounted on the wheel axle being given in fig. 257, and the back view in fig. 258.

Fig. 259 shows the complete truck with the two motors fixed in position on their respective axles and supported from the truck frame. It will thus be seen that the motors are entirely independent of the car, which is carried by the springs shown at both ends of the truck. All the wheels are directly driven, an advantage which is of considerable importance.

Similar but larger motors are used on the Liverpool Overhead Railway, and fig. 260 is very instructive. It shows in a graphic and simple manner the efficiency curves obtained during an exhaustive trial of one of the motors. The horse-power curve is almost a straight line, and the horizontal effort or the pull upon the cars also rises in almost a straight line, but more rapidly than the horse-power. The curve showing the fall in speed as the current rises is interesting, but the efficiency curve is remarkable both for its high value and for its uniformity over a wide range. It will be seen that from about 54 to 160 horse-power the efficiency is never less than 90 per cent.

The method of opening the motor differs from that adopted for tram-car motors, in that the motor frame is divided on the horizontal plane, and the upper half made removable. The field coils are wound with copper

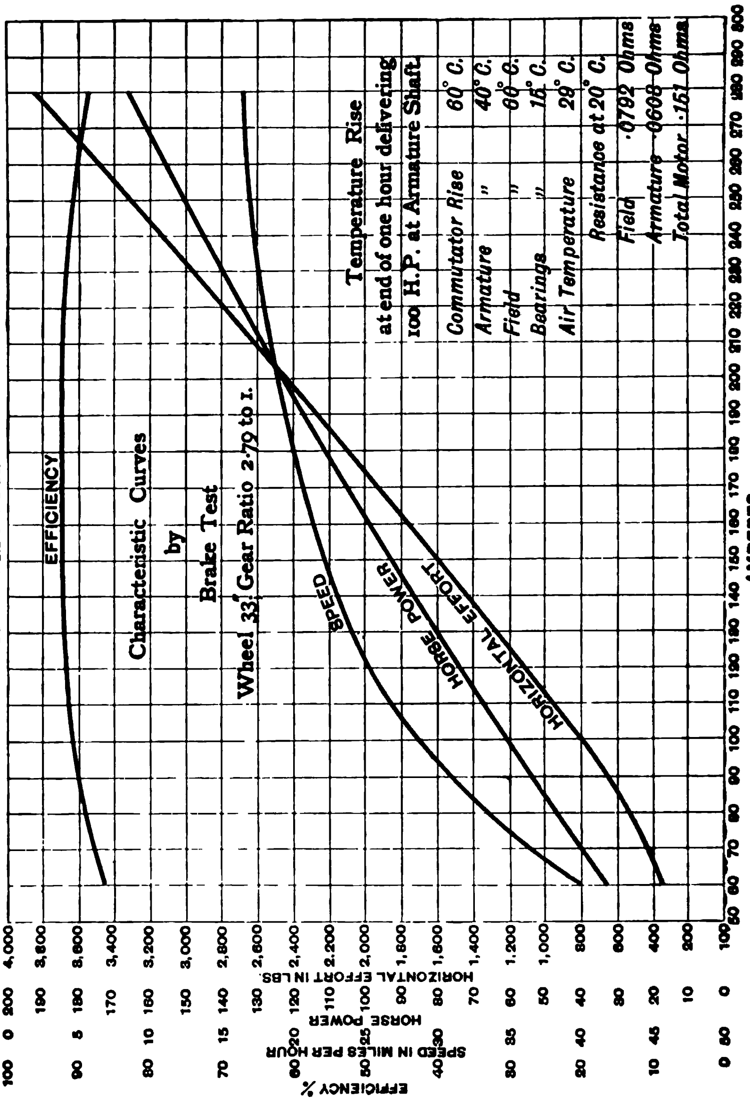
ribbon about 2 inches wide wound with asbestos and mica strip between the convolutions, and insulated over all with mica and asbestos frames, held in position by means of heavy braided tape. Each completed coil is further treated with a waterproof insulating compound and thoroughly baked. The armature core is provided with extra deep slots, and each coil consists of but one convolution, mica and asbestos entering largely into the insulation. The commutator is exceptionally large, so as to avoid sparking and to allow a long run without renewal of the bars. A number of interesting temperature and electrical details are included in fig. 260, and it need only be added that the toothed wheels are of thin cast steel, the teeth being cut out of the solid casting. The pinion in the armature shaft is of hammered machine steel, and the gear-box is of malleable iron made oil-tight. The complete motor with the gearing weighs 4387 lb., or at the rate of 43·8 lb. per horse-power at normal load.

One of the most important items of a car equipment is the controlling switch or 'controller,' by means of which the driver is enabled to start or stop the car, and to obtain the necessary variations in speed. There are a great many varieties of this piece of apparatus, all designed, however, with the same objects in view, viz. to afford a simple and reliable means to enable a non-technical and possibly excited driver to perform alterations in the complicated connections with ease and certainty, and without risk of damaging the motors; and also to avoid, if possible, or at any rate to minimise, the effect of the heavy sparking which is likely to take place at the contact points.

In fig. 261 is shown a 'controller' as made by Messrs. Dick, Kerr & Co. It consists of a vertical barrel P C, with contact points pressing against contact fingers attached to flat springs which are connected to the terminals of the motors, starting resistances, and trolley wire connection, respectively. The rotation of the barrel P C is effected by turning a handle at the top, and the connections are such that the whole of the changes can be made with rather less than a single revolution of the handle. The reversal of the motor, which should rarely be required, is effected by a second handle or lever projecting from the top of the

FIG. 260

100 H.P. MOTOR.



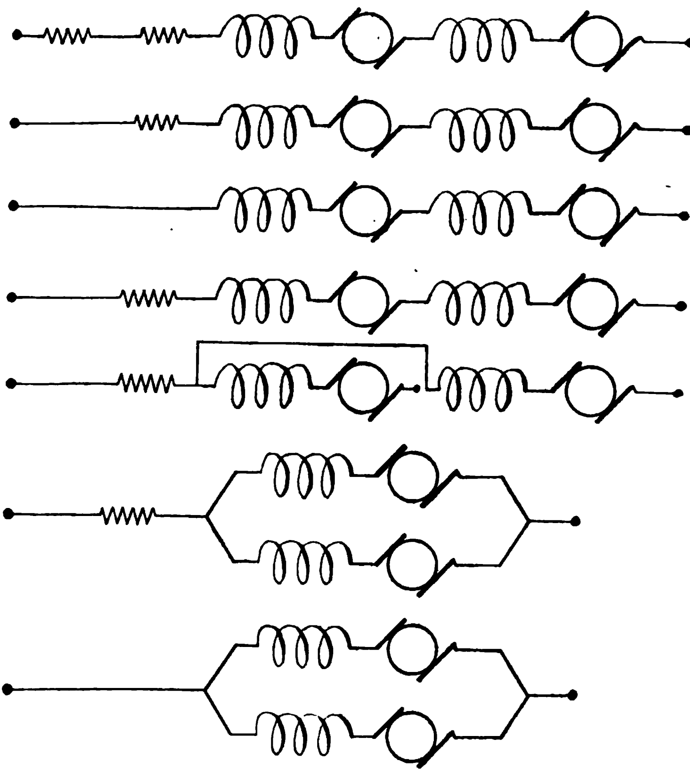
case and attached to the barrel R C. By means of an interlocking device this handle can only be operated when the main switch handle is in such a position that the motors are disconnected from the line. As the main handle is turned and the various contacts are successively broken the tendency for arcing is minimised in an ingeniously simple way. The column S S is a solenoid having an iron core and surrounded by a metal shield. Asbestos collars placed at intervals separate the several contact fingers and prevent the arc from travelling upwards. When an arc is formed it strikes the metal shield on S S. A current in the solenoid S S produces a field in a vertical direction, and by considering the arc as an electric current we know from what has already been said that this current will be repelled by the magnetic field. The result is that the arc travels outwards, becoming longer and longer until finally it breaks, the whole process of 'killing' the arc being very rapid. In some cases an electro-magnet is fixed inside the controller case and so designed that one of the extensions of a divided pole-piece is fixed opposite every point where contact has to be broken, the result being that the arc is 'blown' out. The cylinder B C is used for braking the motor and will be again referred to presently.

FIG. 261

As might be expected, there is a considerable difference in the method of altering the connections of the two motors and the resistance coils which are provided for driving a tramway car, but

the following process, which is illustrated in fig. 262, may be taken as a typical and perhaps the best arrangement. The resistance coils are divided into either two or three sections, and in order to start the car the switch handle is turned on to the first position,

FIG. 262



where it places the two motors in series with each other and with the whole of the resistance. As the speed rises, the handle is turned further, until eventually the whole of the resistance is cut out, the two motors alone being in circuit and still in series with each other. The next step is to place the two motors in parallel,

but manifestly this cannot be done safely with one switch movement, and the usual way is to first insert one or more resistance coils in circuit and then to entirely disconnect one motor ; this disconnected motor can then be joined in parallel with the first one, and when at the next step the whole of the resistance is again cut out, the motors alone are in circuit and are in parallel with each other, and the condition for maximum speed is arrived at. The controlling switch, as stated above, makes all these changes successively with rather less than a single revolution of the handle, but it is, of course, necessary to avoid making the series of changes suddenly ; a short pause, therefore, should be made at each step in order to allow the motors to settle down to the altered conditions. In slowing down, the same changes are made in the reverse order, by turning the handle in the opposite direction. In some instances two additional steps are introduced, one after the motors are in series without resistance in circuit, and the other after they are in parallel without resistance in circuit. The step in each case consists in shunting each field-magnet coil with a resistance coil in order to decrease the field and thereby yet further increase the speed. But this method is not generally employed, because the usual practice is to employ a comparatively small quantity of iron for the field-magnet cores and yoke, chiefly in order to reduce the weight, but partly also with the object of obtaining a field of almost the maximum strength even when the current is considerably below the maximum. Obviously, with a machine so designed, the field strength does not vary greatly with changes in the load, and the rise and fall in torque is chiefly due to the rise and fall of current in the armature, and very little difference can conveniently be effected by shunting the field-magnet coils.

An ordinary hand brake is generally employed in street tramway cars, but an extremely good braking effect can be obtained by disconnecting the motors from the line and then short-circuiting them, the barrel B C in the controller of fig. 261 being provided for the purpose. They will under such conditions act as generators, and the current developed through the low resistance offered by the machines being a very strong one, the resistance to motion becomes very great ; the power is, in fact, approximately

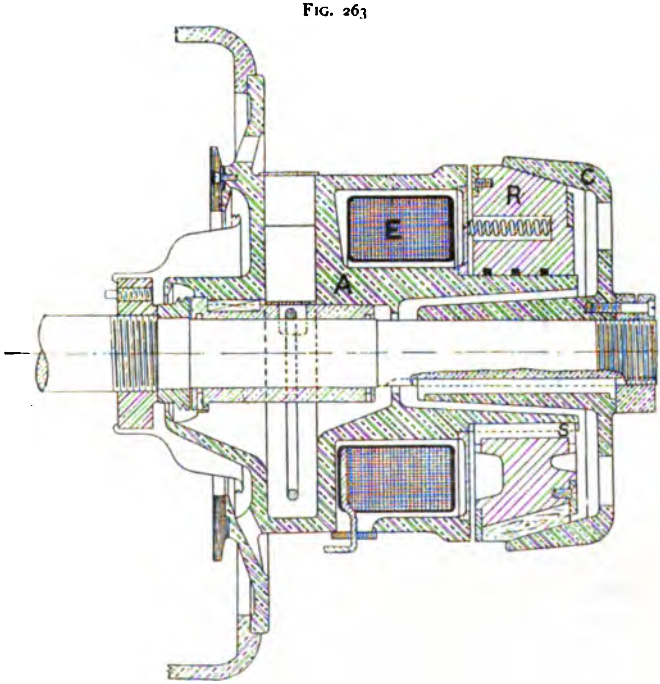
equal to that which would be required to drive the motors as generators to develop the particular currents, and that power is applied in the most effective manner—that is to say, directly on to the car-wheel axle. On account, however, of the severe strain to which this proceeding subjects the motors and gearing when the speed is considerable, this method of braking is only resorted to in cases of emergency, unless, as is occasionally the case, the motors and gearing are specially designed for the purpose. A modification of this method is to arrange an electro-magnet of such a form that it can be applied to the carriage wheel as an ordinary friction brake and at the same time be excited by connecting its winding in series with the machine when acting as generators. There is then a twofold retarding action due to the production of eddy currents in the wheel rim and to the surface friction between the wheel and the brake.

A type of magnetic brake used by Messrs. Dick, Kerr & Co. for crane motors is shown in fig. 263. An extension of the bearing at the commutator end of the shaft carries a malleable iron frame A in which an exciting coil E is placed. The hub of this frame is prolonged to receive a cast-steel conical ring R, which is free to move axially but is prevented from rotating by a key shown at S. Steel springs are fitted to the ring R, which tend to push it away from the magnet frame A. At the extreme end of the motor shaft an iron crown C is keyed, and it is to the inner surface of this that the braking force is applied. When the motor is connected to the power mains the coil E becomes excited and magnetises the frame A. The result is that the ring R is attracted against the force of the springs, and the crown C becomes consequently free to rotate. When the motor circuit is broken the current in E is stopped and the springs push the ring R outwards and thus again apply the brake to the motor shaft.

One of the chief difficulties to be met in electric traction work consists in making satisfactory electrical connection between the travelling car and the conductor or conductors running the whole length of the line and which are permanently joined to the generating machines. If two conductors be employed, one for the lead and one for the return, the necessity for connection with the wheels of the car, the rails, and the earth is avoided, but the

construction is more complicated and much more expensive than when a single conductor and an earthed return are employed, because not only are the attachments and insulators doubled and the conductor doubled in length but the conductor itself must be more massive for a given fall of potential, because there is practically twice the length of conductor in circuit. For these reasons the single conductor system is almost universally adopted.

FIG. 263



One pole of the generating dynamo or dynamos is then permanently connected to the rails and earth, and the other pole to the conductor, which is insulated as effectively as the conditions allow throughout the entire length of the line; a sliding, rubbing, or rolling contact is made between the conductor and a suitable extension carried by the car, by which means the current is led to

one terminal of the motors, the other terminal making earth through the car-wheels, and perhaps also a brush or sliding contact, and the rails.

There are three distinct methods of running the conductor. In the first place it may be carried on insulators in a conduit constructed between the rails, the collector or trailer which makes the necessary sliding contact passing down through a slot in the top of the conduit. In the second method, a third rail insulated throughout its entire length is run between the two car-wheel or running rails and at almost the same level. The third method is that known as the trolley system, in which a hard copper wire is suspended above the track and connection is made by means of a brush or wheel carried on a trolley pole which is supported on the roof of the car. There is an interesting modification of the underground conduit system known as the 'surface contact' system, in which the conductor is automatically connected to the motors under the car by means of a plunger as the car passes over it. These several systems will be more fully dealt with in Chapter XVII.

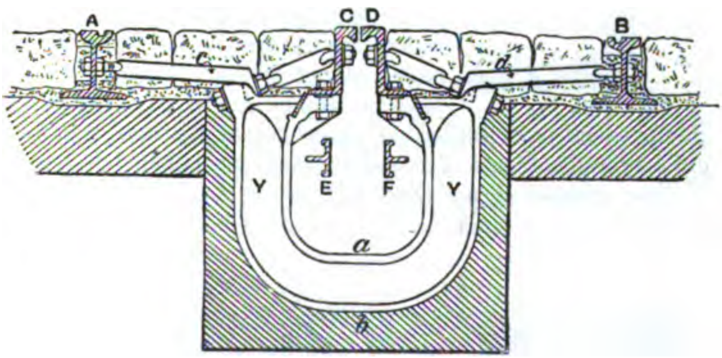
The system laid on the South London tramway service possesses many novel and instructive features. It has been designed in detail by Sir A. B. W. Kennedy, and comprises about 58 miles of double track, running along routes which were previously served by a horse-tramway system. At the time of writing the maximum number of cars in use at one time is 690. The conduit principle has been adopted, notwithstanding its much greater cost as compared with the overhead trolley principle, which is almost universally adopted in Europe, the only other exceptions being on a small scale in Brussels and Berlin. It may interest the student to learn that the prime cost of a trolley line is about 6000*l.* per mile per track, the conduit system costing about 13,500*l.* exclusive of the rails. It has been laid down by competent authorities that the additional expense is warranted on financial grounds, when the traffic suffices to maintain a two-minute car service.

In Sir A. Kennedy's scheme, the conductors are run in a concrete conduit, with heavy cast-iron yokes bedded in the concrete at a distance of 3 ft. 9 in. apart—centre to centre—to

support the 'slot-rails,' and affords a ready means for adjusting the positions of those rails and also of the car-rails. The depth of the conduit from the surface of the road is about 16½ in., and the maximum width 14½ in.

A cross-section of the line through one of the yokes is given in fig. 264. A B are the car-rails resting on a substantial bed of concrete. Y Y is the yoke, which is a massive casting weighing 153 lb.; in section it is H-shaped—that is to say, it consists of an inner stout flange *a* and an outer flange *b*, with an iron web connecting the two together. The inner face of the flange *a* is uniform with the cement lining of the conduit. The upper part

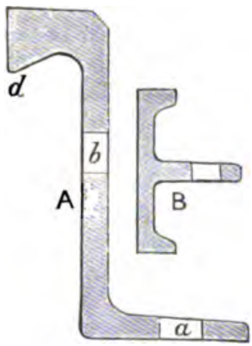
FIG. 264



of the yoke supports the slot-rails C and D, the width of the slot being 0·75 in. A section of one of the slot-rails is given at A in fig. 265. It will be seen that the rail-head is very massive and is provided with a rather sharp edge at *d* to facilitate the dropping of water and mud, and thereby to prevent it creeping down the surface of the yoke. A bolt passing through *a* secures the rail to the upper portion of the yoke, the bolt-hole *b* carrying the tie-bar which, as will be seen in fig. 264, secures the rail to a lug projecting from the corner of the yoke. There are two insulated conductors, E and F, fig. 264, which are ⊣-shaped, as shown in section at B, fig. 265, and are made in 30 ft. lengths. Every alternate yoke is also secured to the car-rails by means of

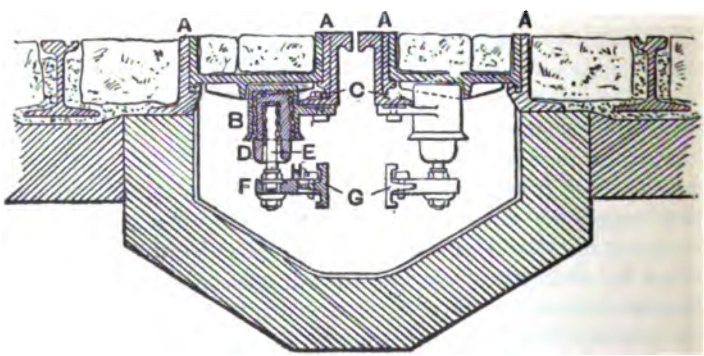
tie-bars, as at *c* and *d*, fig. 264. The iron yoke is, of course, the key of the whole combination, and the alignment of the slot-rails and car-rails is very effectively accomplished by first fixing the ends of the several tie-bars to the yoke, and subsequently adjusting the other ends in the slot-rails and car-rails respectively. This is a marked improvement upon the practice hitherto followed of tieing the car-rails and slot-rails directly together, with the result that the slot-rail was frequently thrown out of line. The roadway is paved with granite, wood being regarded as unsuitable on account of its liability to expand when wet, in which case the slot-rails would probably be forced out of line. Where the road passes a hospital or a church, and where granite would be objectionable on account of the noise made by ordinary traffic, blocks of a hard bituminous compound are used.

FIG. 265



The conductors are fixed well within the conduit, so that anything falling through the slot shall drop between them. The method of supporting the conductors, which are of rolled mild steel, is shown, partly in section, in fig. 266. There is a hand-hole at each side of the slot-rails, and the conduit is enlarged so as to

FIG. 266



give access to the insulators, &c. These hand-holes and insulators are placed at intervals of 15 ft., and as the conductor bars are in 30 ft. lengths, there is a support for each bar at its middle, and another for the junction of two adjacent lengths. The cast-iron box A A, measuring 16 in. by 13 in., rests on one side on the foot of the slot-rail, its other three sides being well supported on concrete. A cast-iron cover rests on this box, and on being removed it exposes to view an iron hood B, which is secured by two bolts to the lower part of the slot-rail, one of these bolts being shown at C. A porcelain insulator, corrugated on the upper portions of its inner and outer surfaces, is fixed into the hood B by means of cement, an iron spindle E being similarly cemented inside the insulator. A horizontal forked clip F is bolted on to the lower end of the spindle E, and the horizontal stem of the ⊣-shaped conductor bar G is placed in the fork and fixed by means of the pin H. It is, of course, essential that the conductor bar should be properly lined up, and in order to effect the necessary adjustment there is a sort of eccentric washer between the shoulder of the spindle and the upper side of the horizontal fork, and by revolving this washer the fork can be urged either forward or backward as may be required.

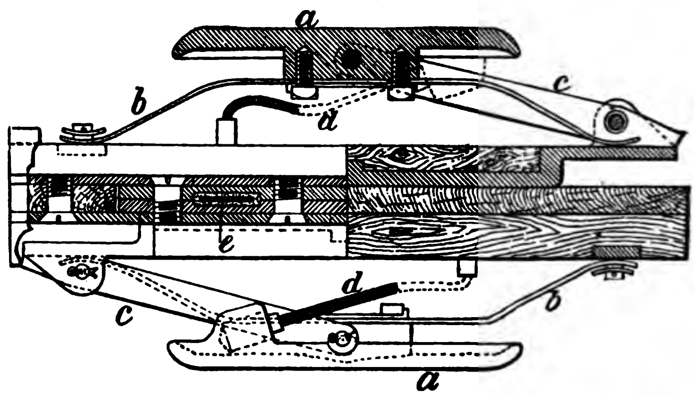
At the alternate insulators provision has to be made for securing the ends of two adjacent conductor bars. This is effected by widening the horizontal fork and providing two pins, one for securing one bar and the second for securing the other bar. In order to secure efficient electrical continuity between the two bar sections there is a pair of copper bonds, wedged by hydraulic pressure into holes near the ends of the bars. The exposed face of the conductor bars is 3½ in. wide, which gives, of course, a good rubbing surface.

At intervals the conductor bars are interrupted for a distance of 8 feet or thereabouts, so that the plough can be dropped into the conduit clear of the conductors, and, by raising the cover provided for these plough-holes, the plough can be withdrawn and replaced if necessary.

Both poles of the generator are led into the conduit, one being connected to one conductor bar, and the other pole to the other bar, so that neither the slot-rails nor the car-rails are utilised

electrically, nor is any part of the electrical circuit earthed. This is an excellent arrangement, but it involves a somewhat elaborate device for the plough, which must, of course, carry two conductors insulated from one another and from the plough itself. A sectional plan of the lower end of the plough is given in fig. 267. There are two rather massive cast-iron contact 'shoes,' *a a*, 7½ in. long and 4 in. wide, which are pressed against the conductor bars by means of the springs *b b*. The distance between the bars is 6 in., but when the plough is free the outer surfaces of the shoes are 7 in. apart, so that the springs cause a fair rubbing pressure between the shoes and the bars, the pressure necessary to

FIG. 267



sufficiently compress the springs being about 8 lb. The shoes are connected to the frame of the plough (consisting of hard wood treated with an insulating waterproof compound) by means of the movable links *c c*. Flexible safety fuses *d d*, which melt or 'blow' when a current of 150 amperes passes through them, convey the current from the shoes to the insulated flat copper strips *e*, which pass up two grooves between a pair of protecting steel plates. These plates when bolted together form the shank of the plough, the conductors being insulated by means of vulcanised indiarubber and tape. The head of the plough is of gun-metal grooved to receive and secure the

shank-plates. Properly protected cables insulated with india-rubber connect the plough conductor strips with the motor, and arrangements are, of course, introduced for releasing the plough from the frame or truck of the car in the event of an obstruction or accident, which might otherwise have serious results.

The generating station is at Greenwich, and occupies a site of 3¾ acres. Usually it is more economical to locate the station somewhere near the centre of the area to be supplied, but in this case the station is near the border of the tramway system which it serves. The drawback on this account is quite compensated for by the fact that the station is by the riverside, and consequently (*a*) an ample supply of river water is available for condensing-purposes, and (*b*) sea-borne coal can be used and delivered direct from the colliers, which are unloaded by electric cranes into trucks which travel along the pier and discharge into a steel bunker on the river bank. Between this bunker and the bunkers in the boiler-house are two conveyers of the bucket type, by means of which the coal is distributed to the furnaces; the conveyers return beneath the firing floor of the boiler-house and provide a means for removing the ashes. The power-house at present is rather less than one-half of its ultimate capacity, but it already contains four three-phase alternator sets, each having an output of 3500 kilowatts at a pressure of 6600 volts with a periodicity of 25 cycles. The alternators are, of course, of the rotating field type, and the stators are star-wound, with the neutral point earthed. The high-pressure current from these machines leaves the station by two groups of 'feeders,' which respectively supply the north and south of London. The feeders terminate in a number of sub-stations, the most remote being about nine miles distant from the station. Each sub-station is fitted with three 500-kilowatt motor-generators of the rotary converter type (see p. 548), which transform the 6600 volts alternating current into a direct current at a pressure of 550 volts for driving the motors under the tram-cars. The ultimate capacity of the generating station is designed to be no less than 34,000 kilowatts. The current from the sub-stations is distributed by means of cables having conductors of copper ranging from 0·2 to

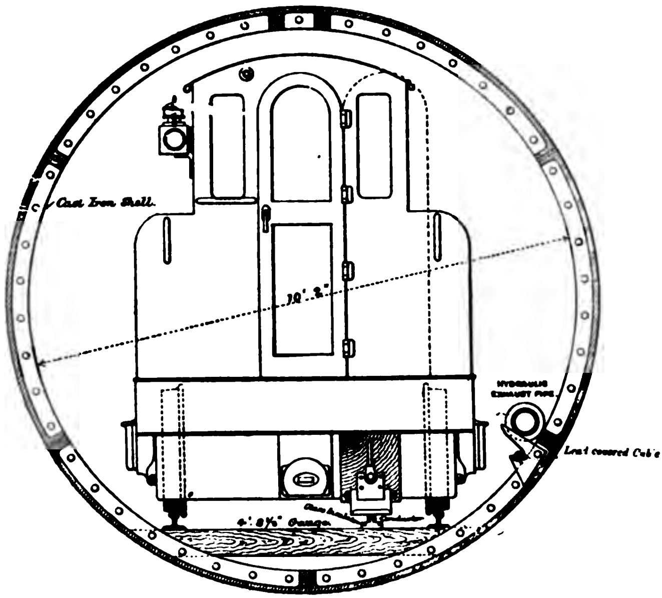
0·7 sq. in. cross-section insulated with paper impregnated with non-volatile oil and sheathed in lead. These cables are run in earthenware ducts bedded in fine cement concrete. The conduit conductor bars are divided into quarter-mile sections with a separate pair of feeders for each section, the ducts along the line being laid between the two tracks. At the division between two sections the ducts and conductors are run from the 'clear way' to a distributing pillar (Chapter XVII.) erected at the edge of the pavement, opposite the sectional division. From these pillars the conductors are run back to the conduit, so that should any accident happen to one sectional conductor, the two sections can be joined together temporarily as a half-mile section, either on both poles or on only one pole, according to circumstances. The system of controlling every electrical connection from the pillars avoids the necessity for running lengths of cable along the conduit itself where it would be liable to damage or to premature deterioration. The motors are made by Messrs. Dick, Kerr & Co., and are of a type similar to those already described, their output being 37 horse-power. Two of these motors are mounted under each car. The resistance coils, which take the form of spirals of high resistance strip-iron wound on metal spiders, the convolutions being separated by asbestos sheet, are placed under the seats of the car, adequate provision being made for the free passage of air currents for cooling-purposes.

An excellent system of drainage has been designed to carry off the surface water direct from the conduits into the drains, and the bottom of the conduit being rounded there is little tendency for mud, &c., to accumulate. Periodic cleanings can, of course, remove any foreign matter that may happen to be left in the conduit. The whole system has been designed with the utmost regard to safety and immunity from breakdown.

It is evident that whenever an intermediate gearing is employed between the armature shaft and the shaft upon which the work is required to be done, some of the power must be wasted, however well the gearing may be designed and made. It is therefore advantageous to avoid such gearing and drive direct from the armature shaft, even though it may perhaps be necessary to employ a slightly less efficient motor for the purpose. The speed at which

the axles of an ordinary tram-car rotate is low, and direct driving at such a speed by means of motors presents many difficulties. Fortunately we have soon learned to appreciate the higher speed at which electric tram-cars usually run; but for electric railway work, where the speed may be considerably higher, the method of direct driving has been successfully carried out. The first application was made by Messrs. Mather & Platt on the City and

FIG. 268



South London Railway. The up and the down lines run in separate tunnels throughout, the tunnels being constructed of cast-iron sections bolted together by internal flanges, as illustrated in fig. 268, which shows a section through the tunnel and an end view of one of the locomotives. The rails are supported on wooden sleepers which fit and rest upon the sides of the tunnel as shown, the gauge being 4 ft. $8\frac{1}{2}$ in. The conductor from which the current is taken is of channel steel supported on glass

insulators and running throughout the line between the two rails, as indicated in the figure, its upper surface being about an inch below that of the rails. The motors are mounted on a separate car or 'locomotive,' each locomotive drawing four passenger carriages. From the bottom of each locomotive three massive cast-iron trailers are hinged; these trailers, which are electrically connected together, slide over the surface of the steel conductor and so collect the current. The conductor is composed of a special kind of mild steel which has a comparatively low specific resistance, the resistance of a mile of the conductor being a little more than a quarter of an ohm. The various lengths are connected with fishplates and bolts, but to ensure a good electrical connection copper strips are also employed, the ends of each strip being riveted to the ends of adjacent lengths of the conductor.

The line was first opened for traffic in 1890, and the total length was $3\frac{1}{3}$ miles. Since then the length has been considerably extended, and a new generating station has been built, the distribution having also been converted from the two wire to the three-wire system (Chapter XVII.) with 1000 volts between the outers, the rails being used as the middle wire.

There are seven sets installed in the generating station, each set being directly and independently driven by a Willans engine. Two of the sets comprise 125-kilowatt generators, one of these being a Siemens bipolar machine, which ran for about six years in the old generating station, the other being an Electrical Construction Company's four-pole generator. Two other sets include 300-kilowatt generators, the armatures of which are each 4 ft. 2 in. in diameter and each machine has six poles, the magnet frame being split into two sections across a horizontal diameter. There is likewise a 400-kilowatt generator whose armature is also 4 ft. 2 in. in diameter, and the magnets have six poles, the yoke being split across a vertical diameter. Finally, there are two 800-kilowatt sets having armatures 10 ft. 8 in. in diameter, whose weight (without shaft) is twenty-eight tons. The field-magnets of these last-mentioned machines are divided into four portions to facilitate handling and have fourteen poles.

There are two sub-stations which are supplied with high-tension continuous current, the pressure being reduced by means of rotary transformers.

The old type of locomotive with Gramme surface-wound armatures has been superseded, and slot-wound machines are now used throughout and have so far proved vastly superior. A further improvement has been the substitution of electric for hydraulic lifts.

The Central London Railway presents several interesting features, the chief being the unusual weight of the trains as compared with previously existing electrical lines, and the remarkable series of transformations which the current undergoes before it is finally conducted to the motors. Each loaded train, drawn by a separate locomotive, weighs about 150 tons. The locomotive is mounted on two four-wheel bogie trucks, the wheels being 42 in. in diameter; a direct-current series-motor is mounted on each axle shaft, driving direct without gearing, each locomotive being thus provided with four motors of about 120 horse-power each. These motors are connected two in series and two in parallel at starting, and they are connected four in parallel when full speed is attained. By this means, and with the aid of resistance coils, a series of sixteen steps is obtained between the positions of rest and full speed. The current is collected by means of trailers under the locomotive, from a 'third rail' fixed with its surface about 1½ in. above that of the rails proper. This third rail is constructed of high conductivity mild steel, of channel section, supported on porcelain insulators.

The current is obtained at the main generating station by means of three-phase alternators, with stationary armatures and a rotating field, the rotating part weighing 34,000 lb. The output of each machine running at 94 revolutions per minute is 850 kilowatts, the pressure being 5000 volts and the periodicity 25 cycles per second. The high-pressure current thus generated is led to three sub-stations along the line, and there transformed, by means of stationary transformers, down to a pressure of 306 volts.

The low-pressure alternating current thus obtained is led to specially designed rotary converters or transformers which take in

the alternating current at 306 volts, and give out a direct current at 500 volts. The current in this form is led to the third rail and thence to the locomotive motors. This railway furnishes one of the most successful examples of the application of electrical power.

Speaking generally, one disadvantage attending the running of motors in parallel circuit, supplied with current at a constant potential, results from the fact that the current carried by the main leading wires is the sum of the currents supplied to the whole of the motors. When the number is great, this main current becomes enormous, and the main conductors or feeders must be correspondingly massive to avoid serious loss of power and fall of pressure; and, of course, the greatest loss and fall occur at the time when they can least be permitted, viz. when the motors are demanding the maximum current. Many difficulties disappear in a system of distribution of power to motors which require to be supplied with a constant current, for all the machines can be joined in series, and the mains need only be of sufficient size to carry the current required by one machine, instead of the whole of them. But other difficulties arise, chiefly in connection with the means available for communicating the current to the motors; sufficiently great, in fact, to make the parallel system, on the whole, more practicable. In fact, although a number of promising systems have been tried, it can hardly be said that series working has yet been successfully accomplished for tramway or railway work. The parallel system is almost universally adopted, and the current to be carried by the mains is kept as low as possible by employing a comparatively high voltage at the motor terminals, and also, if necessary, interposing transforming devices.

Undoubtedly the ideal arrangement is for each vehicle to be entirely self-contained, carrying not only its motor or motors, but also the immediate source of electrical power. For in such a system neither expense nor inconvenience is incurred by any alteration to the existing road, or by the erection of an overhead conductor, with its feeders, &c.; and a host of other attendant inconveniences are obviated. The only practical method of achieving this result is by the aid of secondary batteries. Each battery must consist of a sufficient number of cells to give the required potential

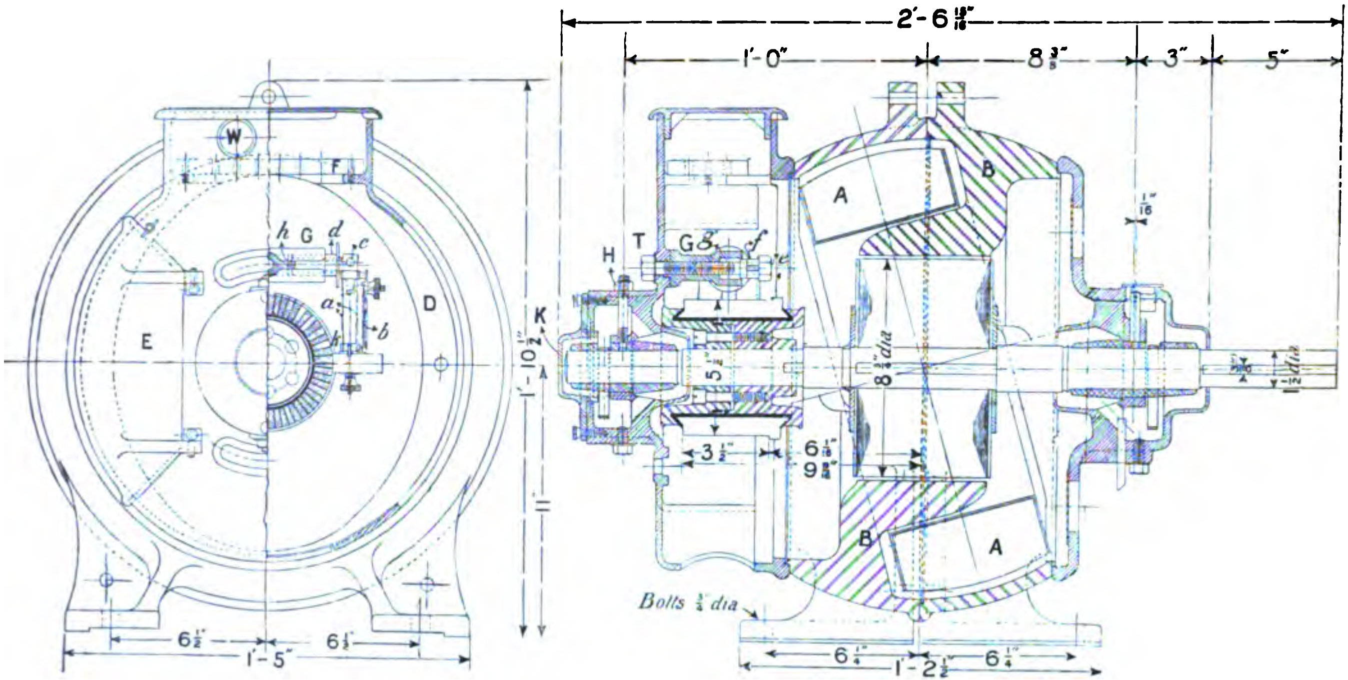
difference at the motor terminals, each cell must be of such a size as will enable it to supply a current of the maximum strength required, and the capacity of the whole battery must be sufficient to enable the vehicle to be propelled with full load for at least one complete journey. As the question of the loss in the mains does not now require to be considered, the necessity for a high potential difference disappears, and consequently a battery of, say, 50 cells, giving a pressure of about 100 volts, will in most cases suffice. With the reduction in pressure there must obviously be a proportional increase in current strength. Hence the cells, although comparatively few in number, must be large and correspondingly heavy. Herein lies the first difficulty to be overcome, because although up to a certain point the increase of weight assists by increasing the adhesion between the wheels and the rails, the minimum increase in weight with an effective secondary battery exceeds this limit, and therefore a considerable proportion of the energy expended is required to carry the battery itself. Efforts have been made to reduce the weight of the non-productive portion of the battery, as well as of the plates themselves; but hitherto this reduction has generally been effected at the expense of mechanical strength and durability, and of electrical capacity. As the conditions are such as to subject the cells to considerable vibration, it is evident that unless they are mechanically strong their life will be but short; and a reduction in electrical capacity involves, of course, a frequent return to the generating station for re-charging. Unfortunately the ideal secondary cell for this class of work remains, and is likely to remain, yet to be produced. It may be mentioned, however, that with a battery of secondary cells a new method of regulation may be adopted; the battery may be divided into several sections and by means of a suitable controlling switch the whole of the sections may be joined in parallel, or in series, or in a combination of series and parallel, thus obtaining a wide range of impressed E.M.F. at the motor terminals. With this arrangement smaller cells than would otherwise be necessary may be employed, because when the minimum impressed E.M.F. is required, as at starting, the current is then heaviest, and the sections being in parallel, this heavy current divides between them, so that the current per cell may be no

higher than that given out when, with all the cells in series, the speed is highest and the current through the motor at a minimum.

A distinct and interesting type of motor which is in general use is the Lundell motor of Messrs. J. H. Holmes & Co. It is illustrated in fig. 269, which gives a longitudinal section of the machine, and an end view partly in section. The characteristic feature of the machine is that it is provided with but one field coil, which excites two poles of unusual shape. The magnet frame is made in two parts, each half being cast solid with one of the poles, as shown at B B in the section. The exciting coil A A is placed obliquely so that when it is in proper position both the poles are embraced by it. It will be understood that the coil is securely held when the two field castings are bolted in position, and that there is therefore no need for any special fixings in order to prevent it from moving: it is sufficient in putting the machine together to simply slip the coil into position, bring the field castings together, and secure the bolts on the outside. Conversely, if it is desired to withdraw the coil, all that is necessary is to unbolt and separate the castings and lift the coil out. The frame is circular on the outside, but it is oval in shape on the inner side, as may be gathered from the end view. The commutator end-plate, which also contains one of the bearings, is bolted on to the facing D. The commutator itself is simple in design, the frame which carries it being made in two parts, which, when screwed together, clamp the segments firmly in position.

Another feature in the machine is the brush holder, which differs in detail from the design adopted with machines of the types already referred to. The main support G consists of a peculiar shaped casting, resembling somewhat the letter **U**, with a long stem or web attached to the lower part. This web is enlarged in the middle in order to allow of a tapped hole which passes right through the web, and carries a screw T, by means of which the casting is secured to the frame. In the channel, *g*, of the section two square tubes of insulating material are fitted, one of them being shown at *d*. The brush holders proper slide into these tubes, and a square insulating washer *h* is screwed on the end, thus preventing the tube *d* from moving relatively to the brush holder. The piece *f* is a webbed bar drilled in the middle,

Fig. 269



2'-6 15/16"
1'-0"
8 3/8"
3"
5"
1/16"
A
B
T
G
H
K
E
D
W
F
h
d
c
a
b
8 3/4" dia
5 1/2"
3 1/2"
6 1/16"
9 3/8"
1'-10 1/2"
11
6 1/2"
1'-5"
6 1/4"
1'-2 1/2"
Bolts 3/4" dia

and which, by means of the screw *e*, allows the two insulation tubes *d* to be clamped into the channel of the casting, and enables the adjustment of the same to be carried out very readily. The copper strips *a* connect the brush box *k* to the main body of the holder, and the necessary pressure of the brush on the commutator is provided by the adjustable strip springs *b*. The brush lead is secured in the socket by a screw, *c*, and carried to the terminal block F. Holes W are provided for the admission of the supply cables, and hand-holes E are provided in the commutator cover to allow of inspection of the commutator and to facilitate the adjustment of the brushes. The commutator bearing is fixed by the stud H, and the end-plate K can be removed to admit oil.

The bore of the magnet poles is $9\frac{1}{8}$ in., and the diameter of the armature is $8\frac{3}{4}$ in., thus giving an air gap of $\frac{3}{16}$ in. The machine shown in the figure is a 6 h.p. motor, and the armature can be wound for any pressure from 100 to 500 volts. The number of conductors necessary for any given pressure between these limits can be calculated, since the magnetic flux per pole is 1·8 million lines, and the speed is from 1000 to 1100 revolutions per minute for the above ratings. The current absorbed can be found, of course, for any given voltage from a knowledge of the efficiency of the machine. The commutator has 56 or 84 segments according to conditions of winding.

An important operation in connection with a dynamo machine is the determination of its commercial efficiency: that is, in the case of a generator, the ratio of the electrical power appearing in the external circuit, and available for useful work, to the total mechanical power spent in driving the machine; and, in the case of a motor, the ratio of the useful mechanical power obtained on the armature shaft, to the total electrical power absorbed. The accurate measurement of the mechanical power in either case presents some difficulty. The usual method is to employ a transmission dynamometer, or a friction brake, to determine the horse-power expended or obtained, as the case may be; but it is difficult with either class of apparatus to be certain of obtaining any but an approximately correct result. The electrical power, on the other hand, can be measured with extreme accuracy, it being

simply necessary to find the current strength in, and the potential difference at the extremities of, the external circuit of a generator; and the current passing through a motor, together with the potential difference at its terminals; the product of the two quantities in either case gives the power in watts.

If it were possible to arrange matters so that it would become essential to measure, by a mechanical process, only a small fraction of the total mechanical power given to a generator, say one-tenth (the other nine-tenths being measured electrically), then a much more accurate result might be obtained; for any error made in measuring this fraction, when distributed over the whole amount, would have but one-tenth the value of that which would otherwise accrue. And, further, it is far easier to accurately determine the value of a small than of a fairly large amount of mechanical power.

An important departure, rendering such a method possible, has been made by Dr. Hopkinson. He takes two approximately equal machines, and, driving one as a generator, leads wires from it to the other, so connected that the current developed by the first machine drives the second as a motor. Now, the mechanical power appearing on the motor shaft is less than that spent on the generator, by an amount equal to the power absorbed by friction, and by the heating of the various conductors, armature cores, &c., in the two machines.

But the power which does appear on the motor-shaft might easily be employed to assist in driving the generator; and this is effected by the simple process of rigidly coupling the shafts of the two machines together; so that the only mechanical power then required to be supplied and measured is an amount equal to that just referred to as being wasted in the various parts of the two machines during the double conversion.

This fraction, thus supplied, is conveniently measured by a dynamometer of the Hefner-Alteneck type which measures directly in pounds the difference between the pull on the tight and slack sides of the driving belt—that is, the actual pull causing the rotation of the pulley. This number, multiplied by the number of feet travelled by the belt per minute, gives the number of foot-pounds of work performed in one minute, which when divided by 33,000 gives us the horse-power supplied by the belt (since

one horse-power is a rate of working equal to 33,000 foot-pounds per minute). With the particular dynamometer employed in one test made by Dr. Hopkinson, the pointer moved over one division of the scale for a pull of 2·705 lb. on the tight side of the belt in excess of that on the slack side, and the radius of the pulley was such that one revolution corresponded to an advance of the belt through 3·63 feet; in this case, then, the work done per revolution was $2·705 \times 3·63$ foot-pounds for one scale-division.

From this it will be seen that if in any experiment T represents the number of scale-divisions traversed by the pointer and n the number of revolutions per minute, then the power applied

$$= \frac{2·705 \times 3·63}{33000} \times n \times T$$
$$= 0·000298 \times n \times T \text{ horse-power.}$$

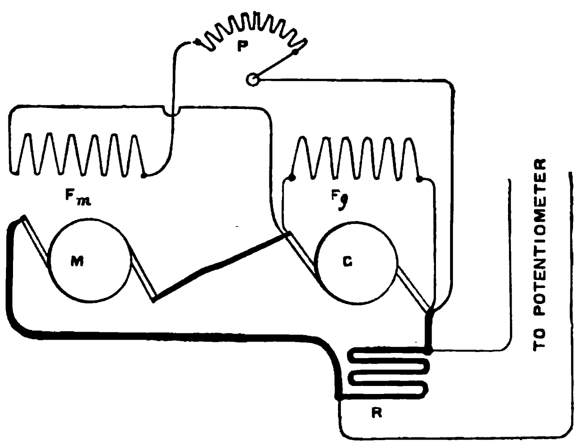
A number of experiments were made with the machines in the case under notice, and as they are interesting, the full results of one test, as furnished by the experimenter, are appended.

The electrical connections were made as in fig. 270, where G and Fg represent the armature and field-magnet of the generator, and M and Fm those of the motor, both the machines being shunt-wound. The heavy lines indicate the main connection between the two machines, and, in order to measure the current, a small accurately known resistance, R, is placed in the main circuit; to the extremities of R are connected wires leading from a potentiometer, by means of which, with a standard primary cell, the potential difference between the ends of the resistance can be accurately measured. This potential difference, divided by the resistance (which was in this case 0·0058 ohm), would give the current flowing through the main wire. The potential difference between the terminals of the generator can be measured by any really good and sensitive voltmeter.

Now, the two machines were exactly alike, and, consequently, if joined in opposition (as two shunt-machines must be, when one is required to drive the other), and then driven at equal speeds, no current would flow from one armature to the other, for they would generate equal E.M.F.'s, or, in other words, the counter

electro-motive force of the motor would be equal to the electro-motive force of the generator. For this reason, it is necessary to weaken the strength of the motor-field, in order to enable a current to be urged through its armature, and this was effected by placing a set of variable resistances, P, in series with the motor field-magnet coils; and, by altering this resistance, the current passing through the motor armature could be varied at pleasure. The motor field-magnet coils, together with P, form a shunt to the generator terminals; the motor armature thus receiving the whole of the current passing through R. Since the resistances of the

FIG. 270



two field-magnet circuits are known, the current in each can readily be calculated after the potential difference at the generator terminals has been measured.

The resistances of the armatures and field-magnet coils of the two machines were :—

Generator . .	Armature . .	0·009947 ohm
	Field-magnets .	16·93 ohms
Motor . . .	Armature . .	0·009947 ohm
	Field-magnets .	16·44 ohms

1. The two dynamos were run with brushes removed and with the fields unexcited.

Scale reading	=	21·6 divisions
Revs. per minute	=	808
Horse-power	=	5·2

2. The two fields were separately excited, and the dynamos driven, still with the brushes off, when

Scale reading	=	30 divisions
Revolutions	=	802
Shunt current in field of generator	=	6·9 amperes
„ „ „ motor .	=	6·7 „
Horse-power	=	7·169

3. The connections were made as in fig. 270, and the following results were obtained :—

E.M.F. at terminals of generator .	=	110·12 volts
Main current	=	358 amperes
Current through generator magnets	=	6·50 „
„ „ motor magnets .	=	5·36 „
E.M.F. at terminals of motor . .	=	107·33 volts
Speed of machines	=	764 revs. per minute
Power transmitted by belt . .	=	6602 watts = 8·850 h.p.

Hence—

Total power given to generator .	=	42917 watts	=	57·53 h.p.
Power lost in armature core . .	=	831 „	=	1·11 „
„ „ generator magnets .	=	716 „	=	0·96 „
„ „ „ armature .	=	1360 „	=	1·823 „

And therefore—

Commercial efficiency . . .	=	93·23 per cent.
Loss in core	=	1·94 „
„ magnets	=	1·66 „
„ armature	=	3·17 „

Similarly for the motor—

Total power given to motor . .	=	38886 watts	=	52·13 h.p.
Power lost in internal friction of core	=	831 ,,	=	1·11 ,,
Power lost in motor magnets .	=	472 ,,	=	0·63 ,,
,, ,, ,, armature .	=	1275 ,,	=	1·70 ,,

And therefore—

Commercial efficiency of motor. .	=	93·37 per cent.
Loss in core	=	2·14 ,,
,, magnets	=	1·22 ,,
,, armature	=	3·27 ,,

The loss due to friction of the bearings and one or two unimportant causes has then to be determined and deducted, to obtain the real commercial efficiency, which, after this deduction, was found to be: motor 92·6 per cent. and generator 92·5 per cent.

One disadvantage of the original method is that it is necessary to have two approximately similar machines in order to perform the test, and this is sometimes inconvenient. A number of modifications of the method have, however, been suggested, the measurement of even a fraction of the power mechanically being in some cases avoided, by obtaining the extra power representing the total waste by means of a small motor, and measuring electrically the amount so supplied.

It is evident that any electric motor may be employed to drive a dynamo machine, and that in this way an electro-motive force, either higher or lower than that applied to the motor terminals, may be obtained with, of course, a corresponding decrease or increase in the current strength. The dynamo shaft may be in line with and rigidly connected to the motor shaft; or to proceed yet a step further, the two armatures may be built up side by side on the same shaft, and the two field-magnets fixed side by side on the same bed-plate. A slight consideration of such a machine will show that the two parts may be yet further combined: that is to say, the two sets of armature conductors may be wound upon

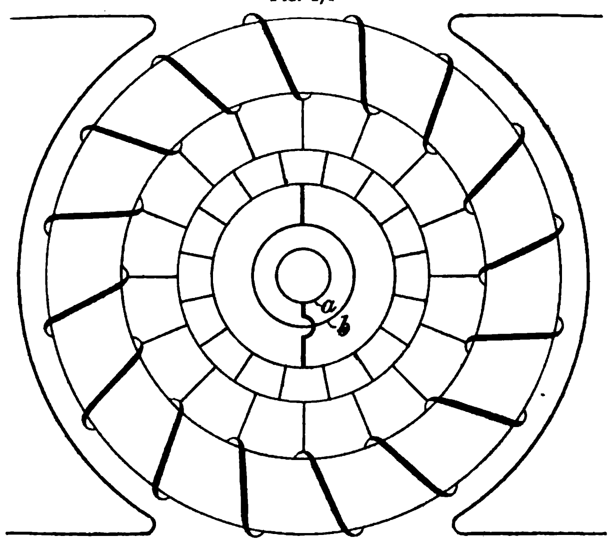
one core, and in that case only one field-magnet becomes necessary. Such a machine is called a motor-dynamo, a dynamotor, or a motor-transformer. The commutators for the two sets of armature connections are generally placed one on each side of the armature, the armature windings being proportioned to suit the particular work for which the machine is intended to be used. If, for example, it is required to obtain a pressure of 100 volts when the potential difference between the mains is 500 volts, the motor portion of the armature should consist of approximately five times as many convolutions as the generator part, because as the same field is employed the ratio of the E.M.F.'s will depend on the number of armature conductors only. The commutator segments and brushes on the motor side would in such a case be less massive than those on the generator side, because the current taken up by the machine as a motor would be considerably smaller than that given out by it as a generator. Such a motor-dynamo will, if properly adjusted at the start, run for a considerable time without requiring much attention, and there need be little difficulty in avoiding sparking at the brushes even though the load may vary considerably, because the ampere-turns in the motor part of the armature are always approximately equal to those in the generator part, and the distortion of the field will consequently be practically neutralised, since a generator-armature always tends to distort the field in the opposite direction to a motor-armature. Further, the self-induction effects in the various motor coils will be to a great extent neutralised by the opposite self-induction effects in the generator coils.

In addition to the conversion of a high into a low voltage current, or a low into a high, it is also possible to convert an alternating into a direct or continuous current, and *vice versâ*, and it now behoves us to consider this question.

In fig. 271 an armature and commutator are shown diagrammatically, and in addition two slip-rings, *a b*, are drawn which are connected to diametrically opposite segments of the commutator. Suppose now that the armature is made to rotate in a magnetic field and that brushes are applied to the commutator (at a diameter which is perpendicular to the axis of the field) and connected to an external resistance. A continuous current will flow in the

circuit, the connections being simply those of an ordinary continuous-current machine. If, however, brushes are applied to the slip-rings, *a* and *b*, a little consideration will show that the potential difference developed between these brushes is alternating, and if connection is made to an external circuit an alternating current will be produced. We thus see that it is possible to obtain a continuous current and an alternating current from the same armature at the same time by providing the necessary slip-ring

FIG. 271



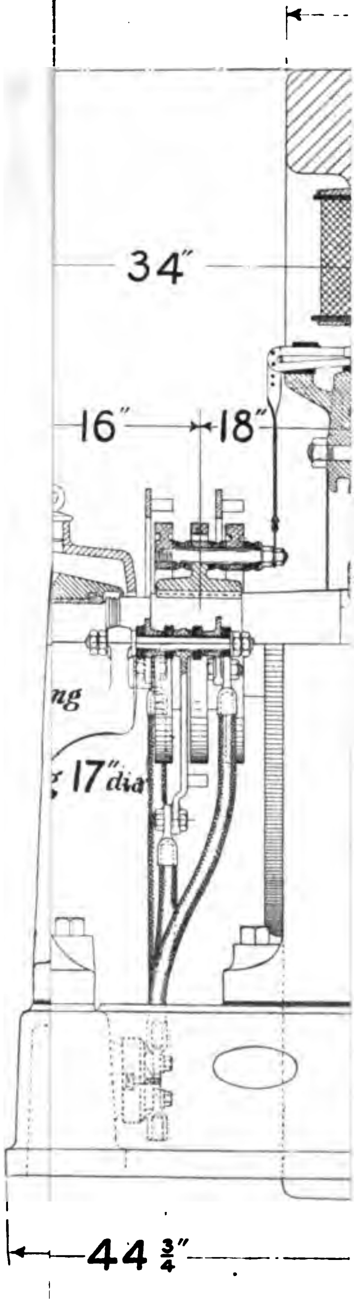
connections. Further, it may be mentioned that an alternating-current generator can be used as a motor if it is first run up to the speed of synchronism and then switched on to the alternating-current mains. Hence if we have a single-phase current and a machine with connections as shown in fig. 271 we can drive the machine as an alternating-current motor and obtain a continuous current from the commutator brushes, or, in other words, such a machine enables us to *convert* an alternating current into a continuous current, or *vice versâ*, and is therefore termed a

rotary converter. By providing three slip-rings, and connecting to three points on the commutator which are respectively 120° (electrical) apart, we may use three-phase currents instead of single-phase, and similarly provision may be made for two-phase currents. These machines are very largely used in the 'sub-stations,' which usually form an important part in the distribution of current over a wide area. Experience has shown that it is much more economical to generate at the central station an alternating current, and transmit it at a high pressure to the sub-stations, transforming (Chapter XIII.) it there to a low-pressure alternating current, and then converting it by means of a machine of the rotary converter type into a continuous current for the supply of tramway systems and other similar purposes.

In rotary converters the armature reaction is comparatively small since the alternating current and continuous current flow in the armature in opposite directions—the alternating current being a motor current, and the continuous current a generator current.

In order to run the machine up to the synchronous speed it is the practice, when batteries are accessible, to start the machine on the continuous-current side as a shunt-wound motor, and then when all is ready to switch off the batteries and connect the slip-rings to the alternating-current mains.

In fig. 272 a rotary converter made by Messrs. Dick, Kerr & Co. is shown by an end view and a longitudinal semi-section. This machine has eight poles, and is designed for a capacity of 450 kilowatts. Three slip-rings are provided on the alternating-current side to which the three-phase current is supplied at a pressure of about 370 volts, and a direct current obtained from the commutator at a pressure of 600 volts. The speed of the machine is 375 revolutions per minute, and since there are eight poles this corresponds to a frequency for the alternating current of $\frac{375}{60} \times 4 = 25$ cycles per second. The armature winding is of the parallel type, and the current is collected from eight brush sets on the commutator. Tappings to the winding are made at intervals of 120 electrical degrees and connections made to the three slip-rings, each slip-ring being


34"
16"
18"
ng
g 17" dia
44 ¾"

connected to every *third* tapping. In this particular case there are four connections between each slip-ring and the armature winding—that is to say, one connection corresponding to each pair of poles.

The field-magnet coils are shunt-wound and are connected normally in series. Arrangements are made, however, to split up the field coils in sections by means of the three-pole switch shown on the magnet frame. The object of this may be briefly explained: When starting the machine up by means of alternating current supplied to the slip-rings, the field coils are short-circuited. The three-phase supply current produces a rotating field (see p. 558), which by its motion across the short-circuited field-magnet coils induces in them alternating currents; and it is the interaction of these induced currents and the current of supply which provides the starting torque to the machine. If, however, all the field-magnet coils were placed in series, and the two ends short-circuited, the high pressure thus induced in them might be sufficient to rupture the insulation, and in order to avoid this the coils are placed in sections in parallel.

In the design of a rotary converter special attention has to be paid to the dimensioning of the sections of the various parts of the magnetic circuit on account of the influence which armature reaction exerts, but these points involve questions of design which it is not desirable that we should further enlarge upon here.

Any one of the alternate-current dynamos described in Chapter VIII. can be used as a motor—that is to say, its moving parts can be caused to rotate, and mechanical power thereby obtained on the armature or field-magnet shaft, as the case may be, by supplying power electrically by means of a suitable *alternating* current. Such machines have some important advantages, and some serious disadvantages. The chief advantages are, first, that the electrical power can better be generated and supplied at a high potential difference with a comparatively small current, thus minimising the loss in the conducting lead; and, secondly, that the machine is perfectly self-regulating as regards speed, in spite of load variations, for it keeps perfect time with the generator. Its speed can be varied by varying the rate of

alternation of the supply current, but this method is inconvenient for obtaining frequent speed alterations, and impracticable if the same generator is supplying more than one motor. Since so much distribution for lighting purposes is now being effected by alternating currents, the necessity for a perfectly satisfactory, simple alternating-current motor is apparent, but up to the present no satisfactory motor is available for general use on such a circuit. The principal disadvantages are that an alternator cannot start itself as readily as can a direct-current motor, but has to be independently driven up to the speed of the generator; while if the load is made excessive the motor is liable to stop entirely and in that case it has to be again started by some external means. The machine will, however, make great efforts to respond to any extra work thrown upon it, and to keep in synchronism with the generator, but will surely fail immediately the load is sufficient to drag it out of unison; and, of course, the fact that the motor can be run at only one speed is in many cases a decided disadvantage. These machines are termed *synchronous* machines, as distinguished from another class of alternating-current motors which always run under the synchronous speed, and are therefore termed *asynchronous* machines, or more usually induction motors. A description of the principle governing the construction of this latter type of motor will be found at the end of the present chapter.

It is extremely inconvenient and requires considerable power to start a large machine, whence any device to facilitate this is very welcome. Perhaps the most practical method yet devised is that due to Mr. Mordey, who employs for the purpose the small machine used to excite the field-magnets. This, as seen, for example in fig. 165, is coupled direct to the main shaft, and, by means of a suitable switching arrangement, its current is at times made to pass through and charge a small secondary battery. When the machine is to be started the current from the battery is passed through the exciter for a minute or two, converting it into a motor which puts the alternate-current machine into rotation. As soon as synchronism between the alternate-current motor and the generator is obtained, the former is switched into circuit and continues to run as a motor.

From these motor properties of an alternator results the very important fact that two independently driven alternating generators can be run in parallel—that is to say, their armatures can be connected in parallel so that the two machines can jointly supply power to the external circuit. It is, however, essential that the two machines shall give the same rate of alternation, and also run co-phasally—that is to say, the maximum positive electromotive force, and also the maximum negative electro-motive force, of the two machines must coincide in point of time. Then the resultant E.M.F. is the same as that of one, while the current in the main circuit and also the power developed will be doubled. Now the remarkable fact is, that the two machines will make great efforts to keep in phase, and will do so, even if the mechanical power supplied to one of them is increased or diminished within reasonable limits. To explain this extremely important mutual action we may remember that the reaction between the armature and field-magnets of a *direct-current* dynamo when used as a generator is such as to tend to stop the rotation, and this tendency becomes stronger as the current in the armature increases, while a weakening of the current of course reduces the resistance to rotation. The speed of a dynamo might therefore be diminished to a certain extent by increasing the current flowing through the armature by some external means; while by inserting an opposing E.M.F. in circuit, and reducing the current, the speed could be increased; and this variation in speed actually does take place in practice unless the engine is controlled by a really good governor. Further, if the opposing E.M.F. exceeded that developed by the machine, the current through the armature would be reversed, and the machine would run as a motor.

Now, these effects can also be obtained with an alternate-current dynamo—that is to say, if the brief currents generated by it are increased in strength, the tendency will be for the machine to slow down, while if an opposing alternating E.M.F. acts in such a manner as to reduce these currents, the machine will quicken its speed; and it will run as a motor, doing work for the moment on the prime mover, if the opposing E.M.F. is sufficient to determine a current in the reverse direction.

Now when two alternators are driven independently, and coupled in parallel, and one begins to lag behind the other, the maximum E.M.F. of the leading machine occurs a moment earlier than that of the other, and consequently a heavy current flows from the leading to the lagging machine for a very brief interval of time. This current, being opposite in direction to that which is then being generated by the lagging machine, tends to drive it as a motor and to accelerate its speed; or if the difference of E.M.F. is not sufficient to set up a reverse current, it weakens the existing one, with the effect of allowing the lagging machine to catch up, as already explained. On the other hand, the later occurring E.M.F. of the lagging machine will tend to increase the current in the leading one and consequently to pull it up. These reactions will commence immediately the alternators tend to get out of phase, and in well-designed machines the effect is so prompt and forcible that they run together perfectly, in spite of inequalities in the driving. It becomes very important, therefore, to decide what qualities and peculiarities a machine should possess to fit it for parallel working. It was for some time supposed that it was absolutely necessary for such a machine to have considerable self-induction, but even then the performance was admitted to be somewhat difficult and uncertain. Consequently, an armature without an iron core, and with few convolutions, was deemed to be undesirable; but these views have been somewhat shaken, and, to a great extent, entirely reversed, by the experiments of Mr. Mordey, who started with the assumption that since the maintenance of synchronism depends upon the motor properties of the two alternators, the machine best fitted for parallel working must be one which possesses these properties to a high degree.

Consequently, the armature should have little resistance, and very little self-induction, and then the transfer of power, by means of brief currents from one machine to the other, which serves to hasten or retard, as required, takes place much more suddenly, and the regulating action is much more prompt and forcible. Of course, the armature will have some self-induction and some resistance, but it is satisfactory to know that neither of these undesirable factors need be made abnormally high, merely for the sake of rendering parallel working practicable.

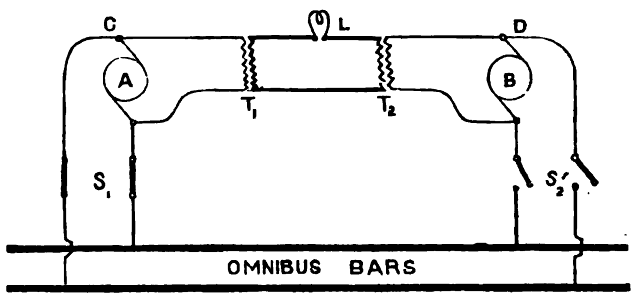
Almost all alternators of modern construction will run satisfactorily in parallel, but it may be noticed that massive rotating parts assist in rendering a machine suitable for this class of work. In any such machine a considerable amount of mechanical inertia tends to prevent any decided variations of speed with the stroke of the engine, and it is also evident that a fairly high speed engine, or, at any rate, one in which the impulses on the crank-shaft are frequent, is best suited for driving alternators which are run in parallel.

Although there can be little doubt that, in the hands of an experienced staff, an alternator having an armature whose resistance and self-induction are low is the most suitable for parallel working, it must be noted that a source of danger results from these low values. For example, should the field-magnet circuit of any one machine be accidentally broken while that machine is feeding a circuit in parallel with other machines, the faulty machine cannot then be driven as a motor, and so set up a counter E.M.F. to prevent the passage of a heavy current; but the high pressure between the mains to which it is connected will immediately urge a heavy current through its armature. So suddenly does the current rise under such conditions that it becomes difficult to protect the armature without using a special safety device, and there is a considerable risk not only of burning up the armature of the faulty machine, but also of seriously injuring those of the other machines feeding the mains. It is comparatively easy to protect an armature having considerable self-induction, as any ordinary fuse will act before the current can rise to a dangerous value in opposition to the self-induction.

In order that two or more machines may be run satisfactorily in parallel, it is preferable, although not absolutely necessary, that they should be of the same type, but in any case it is, of course, essential that they should run at the same rate of alternation and develop the same E.M.F. after they have been switched on to feed the main circuit. The operation of joining in circuit a second alternator in parallel with another already feeding the circuit, is an important one, the objects to be aimed at being to switch the second machine in circuit exactly at the moment when it is in step with the other machine already in

circuit, and to ensure that the incoming machine shall at once begin to take up its share of the load without causing any perceptible variation in the pressure on the mains. A device for indicating when the two alternators are exactly in step or running synchronously is called a synchroniser, and the principle upon which the simplest and most effective type of synchroniser is based may be gathered from fig. 273, which refers to a single-phase machine ; the same method may, however, be employed for three-phase machines by using two of the mains of each machine. The alternator A which is already feeding the main circuit is shown connected up by means of the double pole-switch, S_1 (that is to say, a switch capable of joining up or disconnecting both leads

FIG. 273



simultaneously), to the omnibus bars on the main switch-board. This alternator is likewise connected to the primary coil of a transformer, T_1 (see Chapter XIII.), the secondary coil of the transformer being joined in series with an incandescent lamp L, and the secondary coil of another transformer, T_2 whose primary coil is connected up to the second alternator B, which it is now desired to join up to the omnibus bars.

It will thus be seen that the E.M.F. developed at any instant in the secondary coil of one transformer may be acting either in the same direction round the lamp circuit as the E.M.F. in the secondary coil of the other transformer, or it may be acting in opposition thereto. In the former case the lamp will give out a bright light, and in the latter case it will remain unaffected. The connections

can therefore be so made that when the two alternators are exactly in synchronism—that is to say, when the potential at C is at every instant exactly the same as that at D—the two secondary coils will act together in series and the lamp will glow brightly.

In such a case, the connections being made as shown in the figure, the second alternator B can be steadily driven up to the required speed, the switch S_2 being kept 'open' in order to disconnect the machine from the main circuit. While the speed is still low the lamp will alternate rapidly between brightness and darkness, because during frequently recurring but very brief intervals the E.M.F.'s in the two secondary coils will be alternately acting together and in opposition. As the speeds become more nearly equal, these periods of darkness and light are lengthened, and when the speeds are practically the same the lamp will remain bright, showing that the two machines are absolutely in step. As, however, there is no mutual regulating effort yet brought into play the machines will not remain absolutely in step for any length of time, and in practice the operator simply waits until the lamp remains bright for a few seconds at a time and then closes the switch S_2 at about the middle of a bright period. By regulating the admission of steam to the engine, and also if necessary the exciting current, the in-coming machine may be made to take up its share of the load, as will be indicated by the ammeters placed in circuit with each machine, and the two machines continually keep each other in step as has already been described. It is evident that this method of determining when synchronism has been attained may be varied considerably in details: for example, if the armature is a stationary one, the primary coil of each transformer may be fed from one coil only of the armature instead of being supplied with the full pressure, and further, the connections to the transformers may so be made that the lamp is dark instead of bright when the alternators are synchronous and co-phasal. It is, however, preferable to make the connections so that the incoming machine may be connected up when the lamp is at the point of maximum brilliance.

If the machines have considerable self-induction, and if the armature reaction is great, it frequently happens that the pressure on the main circuit drops appreciably, although the voltage of the

in-coming machine may have been brought up to the full value before it was switched in. This result is chiefly due to the heavy reaction of the armature on the field, the immediate effect being to weaken the field and thereby reduce the voltage of the machine directly it begins to take up a load. One way of avoiding this difficulty is to place a choking coil with great self-induction in circuit between the in-coming alternator and the mains. This coil has sufficient self-induction to prevent the machine developing an appreciable current, and it is adjustable so that its self-induction may be gradually lowered from a maximum down to zero as the machine takes up its share of the load. A second method consists in running the in-coming machine on a temporary load approximately equal to that which it is required to take up before switching the machine in circuit. As the armature reaction then has full play, the field can be excited up to the requisite strength, but machines which require such treatment cannot be considered satisfactory. A well-designed machine with but little self-induction and with little armature reaction can be switched in directly its voltmeter shows that the required E.M.F. has been attained, and the synchroniser indicates that it is in phase, without any prejudicial effect on the main circuit.

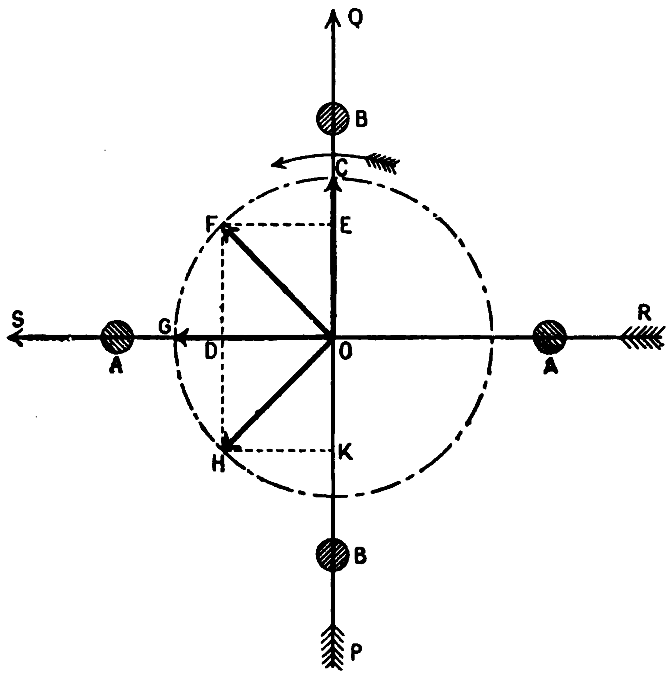
We have explained that although an ordinary single or three-phase alternator can be used as a motor, it can only be so employed in a few special cases because it must first be started by some independent means, and it will then only run at one definite speed, as determined by the frequency of the supply current, and the number of the poles in its own field-magnet. Satisfactory alternating-current motors have, however, been constructed by proceeding on entirely different lines.

The machines to which we refer are termed 'Induction Motors,' because the current or currents supplied from the external source are led through the stator (*i.e.* the fixed part) only, and the rotor is not connected in any way to the supply circuit, but the currents therein necessary to cause rotation are *induced* by the varying field set up by the alternating currents in the stator.

Although the positions might be reversed, the stator is almost universally chosen for the winding which is to be connected to

the mains, because it is so much easier to supply current from an external source to a fixed part than to a moving part of the machine, and the currents in the armature or rotor being induced as mentioned above, there is no need to provide sliding contacts, because these induced currents merely circulate in the rotor windings. We must now consider how it is possible to induce these currents

FIG. 274



in the rotor in such a manner that a continuous turning effect is produced by the interaction between the rotor currents and the field which causes them. It may be stated at once that if the inducing current is a simple, single-phase one, it is not possible to start such a motor to run by means of the currents induced in the rotor ; because the field produced simply oscillates in direction along one line. If, however, the rotor has been run up to

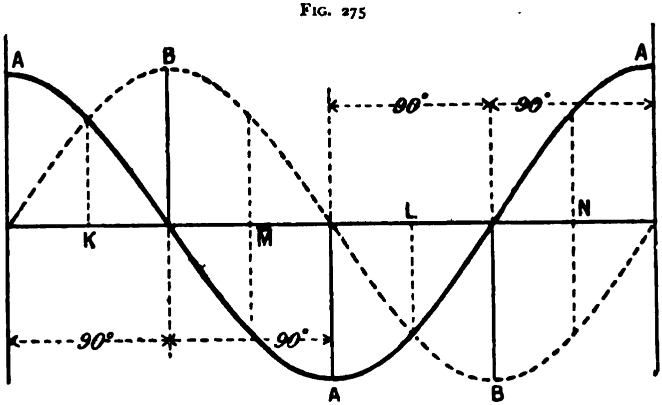
synchronous speed by means of some auxiliary device, and the stator winding be then connected to a single-phase supply, it is a remarkable fact that the machine will continue to run, even when a considerable load is placed on the shaft, and such machines are frequently built.

We have already seen how two and three phase currents may be produced, and have indicated that they have a very important application in practice, viz. the production of a rotating field. We now proceed to consider this application, and the student would do well to read pages 316–319 again before proceeding further. Suppose we have at our disposal a two-phase current; and in the first instance we will assume that the currents are collected from four slip-rings—that is to say, the two circuits are independent. Further, suppose that these currents are led respectively into two coils of wire, which are shown in their simplest form in fig. 274, in which A A represent in section a single coil or loop of wire placed horizontally, and B B a similar coil fixed at right angles thereto. A current passing through the coil A will produce a field in the vertical direction, as represented by the arrowheads P Q, while a similar current in the coil B will set up a field at right angles thereto as indicated by R S. Now what we have to consider is the strength and direction of the *resultant* field produced by these two coils, which will, of course, be determined by the relative values of the respective currents in the two coils at any instant, as indicated in fig. 275, which shows the relative value at any instant of two alternating currents equal as regards their frequency and maximum values, but differing in phase by one quarter of a period, that is by 90°. For example, when A is at its maximum, and B at zero, the field due to A may be represented in strength and direction by the line O C, and this is the resultant field, since the current in B is then zero ; 45° later, as indicated at K, in fig. 275, the two currents are equal. Let O E, in fig. 274, drawn to the same scale as O C, represent the field due to A, then the equal line O D will represent the field produced by B. Complete the parallelogram and we obtain the line O F, which represents the strength and direction of the resultant field at this instant. Similarly, we can find the line O G, which represents the resultant field 45° later still, when B is at its maximum, and A at zero.

It will thus be seen that the resultant field has rotated 90° from the direction O C to the direction O G during a quarter period; and by proceeding further we should find that the resultant field remains constant in magnitude and rotates uniformly about the point O, making a complete revolution for every complete alternation of the currents in the stator coils. O H, for example, corresponds to the point M in fig. 275.

It now remains to be seen how such a rotating field can induce currents in the closed coils of the rotor, always in such a manner that a continual turning effect is produced. Fig. 276 shows the A and B coils embedded in iron to form the stator;

FIG. 275

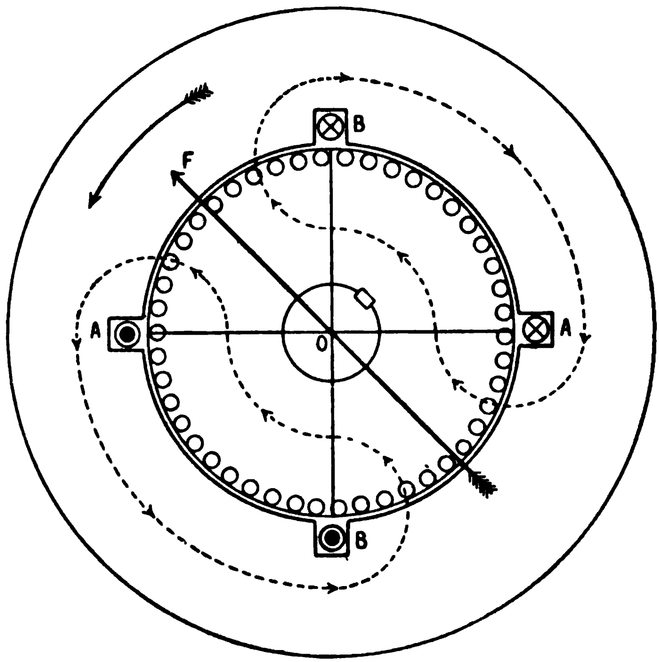


the rotor consisting of a number of conductors embedded in slots round the periphery of a laminated-iron drum, all these conductors being connected together by a conducting ring at each end, the construction thus being similar to that of a squirrel cage.

Supposing the rotor to be at rest, it is evident that the resultant field (as indicated at one moment by the line O F) is cutting these conductors at right angles as it rotates. The currents induced thereby in the rotor conductors follow the universal law: that is to say, they are in such a direction that they strive to stop the motion of that which moves—in this case the resultant field. The field, however, continues to rotate, and consequently the result is a pull on the rotor, which, being free to rotate, is pulled round in

the direction that the field revolves. Now immediately the rotor begins to follow the field, the rate at which its conductors are cut by the field is reduced, and consequently the currents induced in the rotor coils are decreased in strength, thus reducing the pull, and this reduction becomes greater as the speed of the rotor is increased. At first sight, therefore, it would appear that

FIG. 276



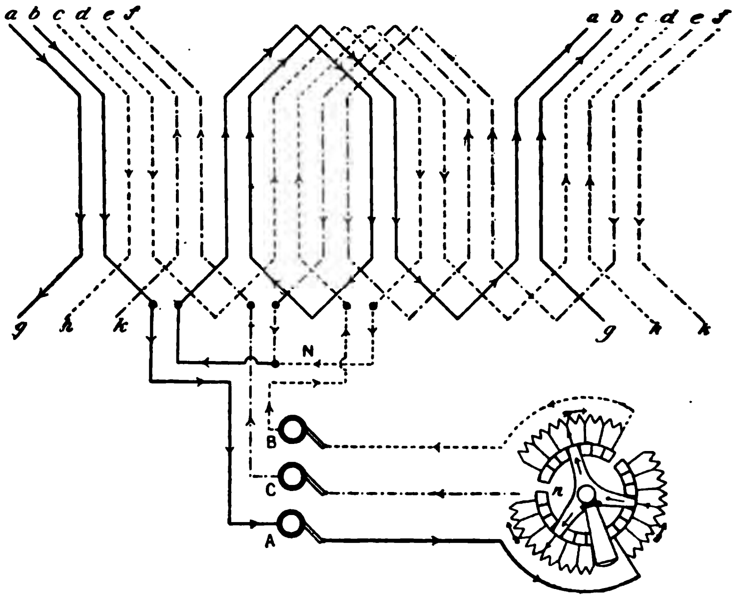
such an induction motor has the valuable property that the torque or turning effort is greatest at the moment of starting, and that the torque is increased whenever the rotor speed is reduced by increasing the load. This, however, is not the case, as will presently be seen. It is manifest that the rotor must always rotate at a speed somewhat less than that of the field ; if the speeds were equal the rotor conductors would not be cut by the field, and

no current would be induced. The difference in speed of the rotating field and the rotor conductors is termed the *slip*, and is usually expressed as a percentage of the speed of the field. Thus if the field rotates at the rate of n_1 revolutions per second, and the rotor makes n_2 revolutions per second, the slip will be $\frac{n_1 - n_2}{n_1} \times 100$ per cent. When the machine is at rest the slip of the rotor is 100 per cent., and when running at synchronous speed the slip is zero. In practice it is found that the slip of a large induction motor is about 2 or 3 per cent. when the machine is working at full load; but the slip is greater in the case of smaller machines, being about 10 per cent. for a one-horse-power motor.

It is evident that in order to obtain an efficient machine the resistance of the rotor conductors must be kept very low. The result of this, however, is that when the rotor is stationary enormous currents are induced therein; in fact, the machine then acts simply as a transformer, with its secondary coil short-circuited, and, as the student will learn from Chapter XIII., the heavy secondary currents react on the primary circuit—that is, the stator or field coils—in such a way as to reduce their effective self induction. In other words, the counter E.M.F. of the field coils is considerably reduced, with the result that the impressed E.M.F. can send through them a current very much above the normal strength. A serious reduction of the pressure in the mains might thus be caused by starting a motor. Further, as we have just mentioned, since the rotor conductors are comparatively short and massive, and as their ends are connected together (generally by massive copper rings in the squirrel-cage formation already referred to), their resistance is extremely low; moreover, since they are embedded in iron, the self-induction, as compared with the resistance, is relatively enormous, so great in fact that the maximum value of the induced currents and their phase will be determined almost entirely by the self-induction and not by the resistance. This is especially the case at starting, because then the frequency of the induced currents is at its maximum, being equal to the frequency of the supply current. As the rotor increases in speed the frequency of the induced current becomes less, and then the self-induction effect becomes of less and less importance.

It is shown in Chapter XIII. that the effect of self-induction is not only to reduce the value of the current strength, but also to retard it or throw the current out of phase with the E.M.F. In the case of the rotor coils under consideration the E.M.F. is caused by, and is in synchronism with, the rotating resultant field, and if the rotor current lags behind the induced E.M.F., it lags similarly behind the rotating field, with the result that the torque is correspondingly

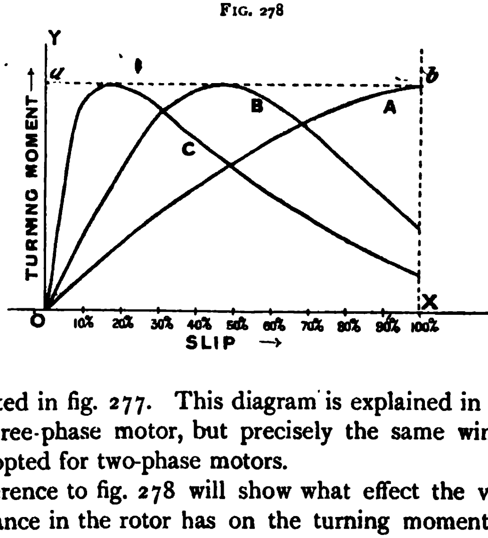
FIG. 277



reduced. It is therefore useless to obtain very heavy currents in the rotor if they are out of phase with the resultant field, and this it will be seen happens when the rotor is at rest. This difficulty at starting can be overcome by increasing the resistance of the rotor winding, thus reducing the relative value of the self-induction as compared with the resistance. In small machines this is sometimes effected by connecting the rotor conductors by means of rings of German silver or some other alloy instead of copper, and

it is unnecessary to point out that the efficiency of the machine is thereby somewhat reduced. In larger machines this method of procedure is impracticable, and it is found necessary at starting to temporarily insert resistance in series with the rotor windings, cutting this resistance out as the speed rises. When this is done the simple squirrel-cage method of winding has to be abandoned, the rotor then being wound on the drum principle in several sections, generally three. To enable the resistance to be inserted or cut out of circuit, as may be desired, it is necessary to connect the ends of the rotor sections to contact rings fixed on the shaft, connection being made with these rings by means of brushes in the usual way. The exact method of introducing this resistance

FIG. 278



is illustrated in fig. 277. This diagram is explained in connection with a three-phase motor, but precisely the same winding is as a rule adopted for two-phase motors.

A reference to fig. 278 will show what effect the variation of the resistance in the rotor has on the turning moment when the machine is starting up. In this figure the turning moment is plotted along the vertical line O Y, and the slip along the horizontal line O X. Thus the point X corresponds to 100 per cent. slip—that is to say, the rotor at rest, and the point O corresponds to synchronous speed. The curve A shows the relationship of the turning moment and the slip when the resistance in the rotor circuit is large; the curve B is drawn for a smaller resistance,

O O 2

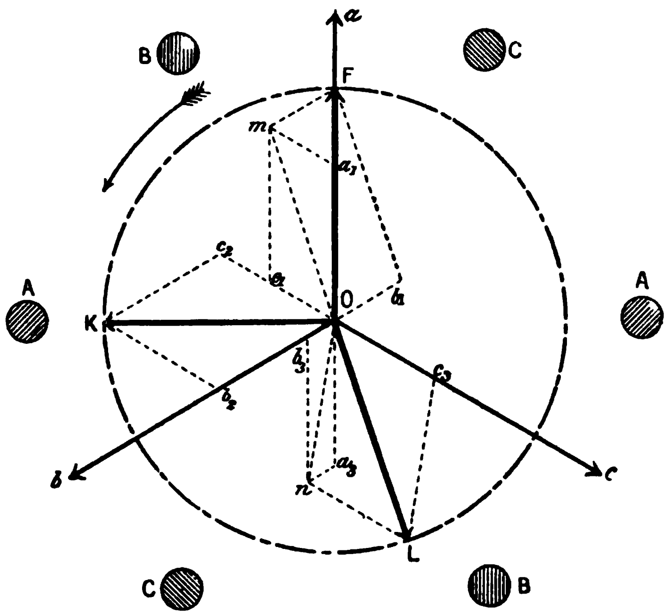
and curve C corresponds to normal working conditions in which the only resistance in circuit is that of the conductors themselves. It is to be noticed that in the case of curve A the maximum turning moment occurs when the machine is at rest, and this enables the motor to start up with a good torque. After reaching a certain speed some resistance is cut out of circuit and the conditions are represented by curve B in which the maximum turning moment occurs at about half the synchronous speed and the motor continues to accelerate its speed. Finally, all the resistance is short-circuited and the speed reaches a value depending on the extent of the load. If the motor is loaded to such an extent that the turning moment required to drive it exceeds the maximum turning moment which the machine is capable of exerting as shown by the line *a b*, it will rapidly come to a standstill. Usually an induction motor can exert a turning moment about 50 per cent. higher than the normal turning moment for which it has been designed. In the case of squirrel-cage rotors the above method of starting cannot, of course, be used, but in this case it is possible to prevent an excessive rush of current and to obtain a good turning moment by inserting resistance in the stator winding. Induction motors have the great advantage that they are extremely strong and will stand rough usage, whilst their simplicity of construction renders them less liable to breakdown than, for instance, a continuous-current machine, where the commutator is in many cases a weak point. Moreover, since squirrel-cage induction-motors have no moving contacts they can be completely enclosed and made weather-proof, and, if necessary, even air-tight also, which is sometimes a very desirable feature.

The two sets of stator windings necessary for a two-phase motor are generally kept quite distinct, two pairs of main leads being employed. In some cases, however, one end of each winding is connected to a common return wire, thus reducing the number of mains to three, with a consequent slight saving of copper in the main leads. The current in the third or return wire is at any instant equal to the algebraic sum of the currents in the other two wires, and may be deduced from the curves in fig. 275. The amplitude of the current in the return wire measured in

amperes is, as a matter of fact, equal to the amplitude of the current in either of the other two conductors multiplied by $\sqrt{2}$.

The general principles underlying three-phase motors are similar to those already explained for two-phase machines. It is necessary for the generator to produce three distinct alternating currents differing in phase by 120° as shown in fig. 154, and a brief study of these curves has already been given (Chapter VIII.).

FIG. 279

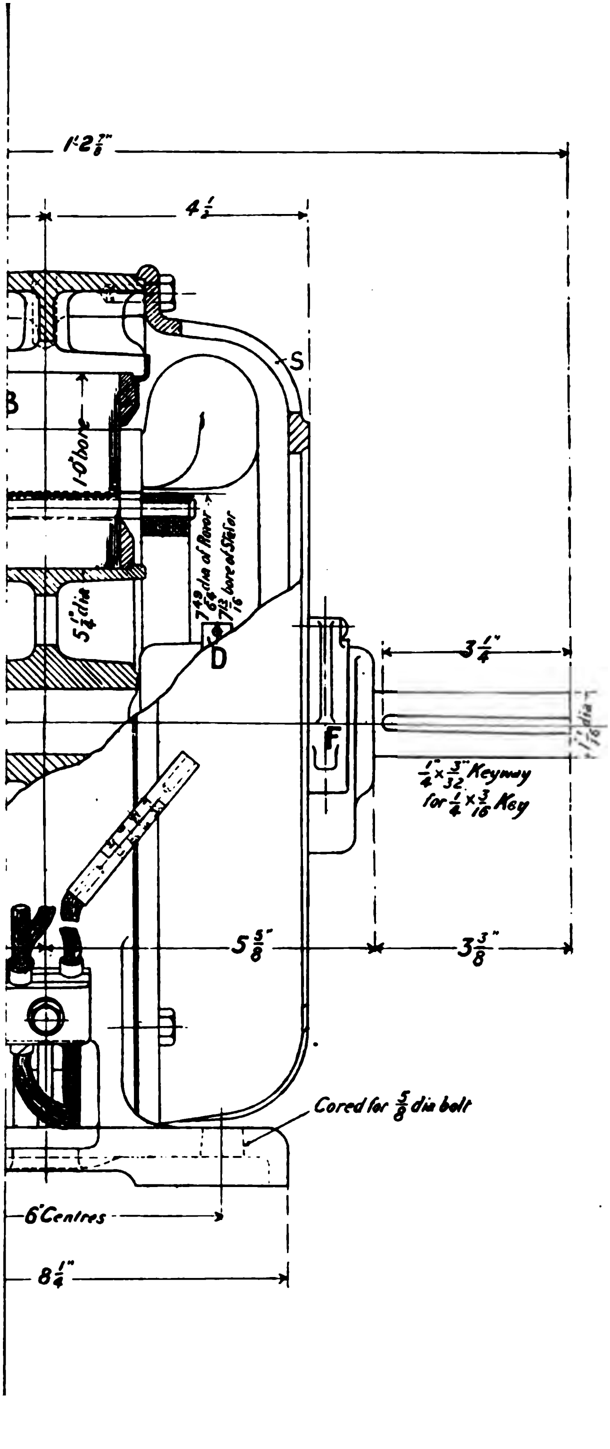


If the stator coils are symmetrically placed it may be shown that the three-phase current will also produce a rotating resultant field similar to that set up in a two-phase machine. In fig. 279 the three sets of coils are indicated by sections of single loops of wire at A A, B B, and C C, symmetrically placed round a circle. The field set up by each loop alone would be at right angles to the plane of that loop, and the *positive* direction can be represented by the lines O *a*, O *b*, and O *c* respectively. We have now to

consider how the resultant field varies when the currents in the coils vary as indicated in fig. 154. For example, when the current in A is at its maximum and positive, and B and C are both *negative* and equal, as shown at F in fig. 154, then the resultant field is represented by O F in fig. 279. O c_1 represents in magnitude and direction the field due to C at this instant, and O a_1 that due to A. By combining these we get the resultant O m; O b_1 represents the field due to B, and by combining this with O m we obtain the resultant of the three fields, viz. O F. 90° later, as shown at K in fig. 154, A is at zero, and we then get the resultant field by simply combining the fields due to B and C, which are equal in strength, although the currents are opposite in direction. The fields will not be opposite in direction because the coils are fixed in different planes. The field due to B is now represented by O b_2, and that due to C, which is now in the negative direction, by O c_2, and by combining the two, by means of the parallelogram of forces as before, we obtain the resultant O K. Similarly O L, corresponding to the point marked L in fig. 154, may be found, and the student will find by the same methods that the resultant field always has the same numerical value, but rotates uniformly about the centre O, in a left-handed direction as indicated by the curved arrow. Moreover, it will be found that the magnitude of this resultant field is 1·5 times as large as the maximum value of any of the three component fields; O F, for example, being 1·5 times O a_1.

This rotating resultant field will cut the rotor conductors, inducing currents therein in the right direction to cause rotation, exactly after the manner described for the two-phase machine. For the purpose of introducing resistance at starting, one end of each of the three windings on the rotor is connected to a contact ring on the shaft (the other three ends being connected to a common junction, as already explained). Each brush is connected to the free end of one of the three resistance coils, the other ends thereof being connected together.

This is shown in fig. 277, where the complete three-phase rotor winding is given for a four-pole machine. It must be understood that the points a b c, &c., on the right-hand side are connected directly to the similarly lettered points on the left-hand side to form the complete winding. One neutral point is



1'2 7/8"
4 1/2
S
B
1-0" bore
7 49/64 dia of Rotor
7 13/16 bore of Stator
5 1/4" dia
D
3 1/4"
1 1/16" dia
F
1/4" × 3/32" Keyway
for 1/4 × 3/16 Key
5 5/8"
3 3/8"
Cored for 5/8 dia bolt
6" Centres
8 1/4"

shown at N, and the other will always be at *n*, which is the three-armed bar forming the movable switch contact. One end of each rotor winding is connected to its proper contact ring, A, B, or C, fixed on the shaft, and the currents are taken off by brushes to the three sets of resistance coils, the manner in which the resistance may be cut out being clearly shown in the diagram, where half the resistance is shown in circuit. By turning the switch further to the right the whole of the resistance can be cut out, and this would be the normal working position at full load.

In fig. 280 is illustrated a 'squirrel cage' induction motor as constructed by the British Westinghouse Company. The stator frame consists of a webbed cast-iron structure, A, which supports the stator core laminations, B. Two cast-iron rings, C C', clamp the core discs together, the ring C' fitting against a shoulder on the frame seating, and the ring C being kept in position by keys at regular intervals. A layer of insulating material is placed over both these rings in order to prevent the stator coils from coming into contact with them. The bore of the stator is $7\frac{13}{16}$ in., and the diameter of the rotor core is $7\frac{49}{64}$ in., thus allowing only $\frac{3}{128}$ in. for the clearance between the stator and rotor surfaces. It is, in fact, characteristic of induction motors that the air-gap is extremely small, the limit being determined by mechanical considerations only. The rotor core discs are built upon a cast-iron spider and secured in a similar manner to that employed for the stator discs. The end-plates, S S, of the machine are secured by four bolts to the frame, and the bearings are held in position by means of the dowel-pins, D D. Lubrication is effectively performed by rings, E, which dip in the oil-baths, the oil being supplied through holes which are protected by the covers F F. Ventilation of the various parts is sufficiently provided for by the perforations in the end-plates and rotor spider.

With regard to the winding of these machines, the stator of the motor shown in the figure can be wound for any frequency for either two- or three-phase currents, and for any pressure up to 600 volts. For instance, one typical winding is for 3 h.-p. at a supply pressure of 400 volts and three-phase currents, the speed being 1400 revolutions per minute. The winding would be so

carried out that the number of poles would for the desired frequency correspond to this speed. Thus if the stator coils were wound so that the sides were at opposite ends of a diameter, the winding would give two poles in the stator, and for three-phase currents each coil must be displaced on the periphery by 120° relatively to the others. This would then correspond to a frequency of supply of 23·3 cycles per second. The winding of the stator would, for the rating given above, be distributed in forty-eight slots in the stator, each slot having forty-six conductors. The rotor would then have thirty-nine slots with one conductor per slot, the ends of these conductors being short-circuited by the copper rings, G G, as in the usual 'squirrel-cage' arrangement. It is to be noticed that the construction of induction motors is extremely simple and strong, from a mechanical point of view, and they can therefore withstand a great deal of rough usage. One disadvantage in employing this type of motor is the difficulty with which the speed may be regulated, for it has already been pointed out that the speed is determined (within a small percentage dependent on the load) by the frequency of the supply current and the number of poles for which the stator is wound. When two or more motors are employed it is possible to reduce the speed to a definite fraction of that deduced from the frequency of supply by connecting them up so that the rotor of one motor feeds the stator of the next, and so on; the stator of the first motor being fed by the supply mains, and the rotor of the last being short-circuited. This method can, of course, only be adopted when the rotors have windings which are connected to slip-rings and not short-circuited—that is to say, when the rotors are 'wound,' as distinguished from 'squirrel-cage,' rotors.

CHAPTER XIII

TRANSFORMERS

WHEN it is desired to convey energy to a distance by means of electricity, either for the purpose of producing light or mechanical motion, the chief problem to be faced is, how to reduce to a minimum the waste of energy during the transmission. We have seen that when a wire is used to convey a current, the rate at which energy is lost in that wire can be measured by multiplying together the current strength in amperes and the difference of potential between the ends of the wire in volts, the result being the number of watts so expended. And since the potential difference is equal to the product of the resistance of the wire and the current flowing, the loss in watts may also be calculated as the product of the resistance and the *square* of the current strength. That is to say, in the first place the power expended in any part of a circuit is proportional to the resistance of that part. Suppose, for example, a dynamo were employed to furnish current to a number of lamps arranged in parallel, their joint resistance being 10 ohms; then if the resistance of the machine and leads or connecting wires were also 10 ohms, exactly as much power would be wasted as would be usefully expended in the lamps, a state of affairs which manifestly could not be tolerated. If the resistance of the machine and leads were reduced to 1 ohm, then the power wasted would be one-tenth of that usefully employed, and so on.

The resistance of the combination to which power has to be supplied is, as a rule, extremely low; and when the lamps or motors are joined in parallel, the current carried by the mains is equal to the sum of that required by the whole of the lamps or motors. Consequently the resistance of these mains must be kept extremely

low, a small fraction of an ohm, in fact, otherwise the proportion which the power wasted bears to the total quantity of power developed becomes excessive. To keep the resistance low, copper of high conductivity must always be employed, but the practical limit as regards sectional area is quickly reached on account of the high price of that metal.

Speaking generally, it may be said that transmission of energy to any considerable distance by electricity is not economical, if we depend upon the reduction of waste merely by increasing the conductivity of the leads. Again stating the case as:

$$\text{Watts lost} = \text{C}^2\text{R},$$

where R is the combined resistance of the leads and generator, we see that the only other way out of the difficulty is to reduce the current strength. If this can be done the advantage is very decided; for, by halving the current, the power wasted in any portion of the circuit is reduced to one-fourth. It may not, however, be evident at first sight, how with this reduced current the same amount of energy can be transmitted in an equal time.

Digressing for a moment, in order to introduce an analogy, the student will probably be aware that in transmitting power mechanically to a distance by a slowly moving cable or rope, it is imperative that the cable and the rest of the moving parts shall be very strong and massive, and consequently the power lost by friction, &c., becomes enormous. Now the energy transmitted per minute is equal to the pull on the cable in pounds, multiplied by the distance in feet through which the cable moves in a minute; so that, by increasing the velocity of the cable, the pull thereon can be reduced, and the strength and size of the cable and of the other moving parts can be correspondingly diminished, without reducing the amount of energy transmitted per minute. It is, in fact, possible to transmit enormous power by means of a light wire cable, if it travels with sufficient rapidity; and the loss due to friction is also reduced with the reduction in size and weight of the moving parts. Even if it is essential for the power so transmitted to be taken for actual use from a slowly rotating shaft, it is still economical to transmit it at a high velocity, and effect the necessary reduction in speed by suitable gearing.

Somewhat similarly, very great power can be conveyed electrically by a comparatively small current traversing a thin wire, if only the electric pressure or potential difference is sufficiently high; for the power in watts may be calculated as the product of these two factors (current strength and potential difference), and no difference in the amount is made by reducing one of them, if the other is increased in like proportion.

But unfortunately it rarely happens that electrical power can be utilised at a high pressure; for instance, 240 volts is usually the maximum pressure required by a set of incandescent lamps joined up in parallel, and consequently it becomes necessary to employ, if possible, some arrangement which shall perform the same function as does mechanical gearing in reducing speed. That is to say, we require some apparatus competent to receive electrical power in the form of a small current at a high potential difference, and again give out that power in the form of a heavy current, and at a correspondingly lower potential difference.

It is possible to construct such apparatus; and before proceeding further we may notice the two chief points to be borne in mind in designing it:

1. The proportions of the parts must be so calculated that the reduction is effected in the desired ratio; or, the value of the resulting potential difference must be the required fraction of that applied to the apparatus.

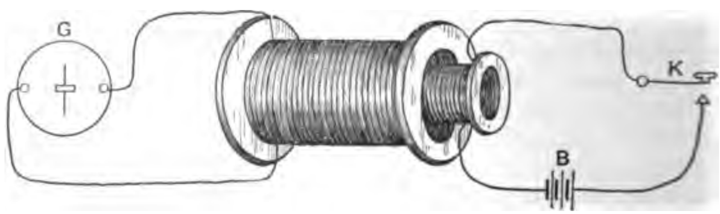
2. The loss in power during the conversion must be kept as low as practicable—that is to say, the design must be such that the efficiency of the apparatus is high.

The conversion from a high to a lower potential is rendered possible by the fact, already fully explained, that by starting or stopping a current in a circuit, a brief current can be induced in a neighbouring wire. The circuit in which the original current is started or stopped is called the 'primary' circuit, while that in which the currents are induced is called the 'secondary' circuit.

For example, in fig. 281, where two coils of wire are shown one placed inside the other, the inner coil with the battery B and key K constitute the primary circuit, and the outer coil and galvanometer G the secondary circuit. The two coils are electrically insulated one from the other, yet on closing the key and

starting a current through the inner coil, a momentary current would be induced in the outer coil, and the existence of this current would be indicated by a sudden brief deflection of the galvanometer needle. The needle would then return to zero, showing that the current in the outer or secondary coil had ceased, although the primary current would still be flowing at its full strength, and we know that this cessation of the secondary current is due to the fact that the lines of force generated by the current in the inner coil are now stationary, and therefore produce no effect on the outer coil although many of them still embrace the convolutions of that coil. On raising the key, however, and breaking the primary circuit, the galvanometer needle would again be momentarily deflected, but this time in the opposite direction, and the momentary current causing this deflection is

FIG. 281



generated by the above-mentioned lines of force, which, in collapsing upon the primary coil, again cut the convolutions of the secondary coil, but in the opposite direction.

In order to obtain the maximum effect for a given primary current it is necessary to ensure that the secondary coil is cut by as many as possible of the lines of force generated by the primary coil. The best method of attaining this desired result is to provide plenty of iron in the vicinity of the coils, not only in the form of a straight core passing through both coils, but so disposed that it forms a closed magnetic circuit entirely embracing both coils. By this means nearly all the lines of force generated by the primary coil may be made to embrace the secondary coil. It should be unnecessary to state that no iron must be placed *between* the two coils if the maximum E.M.F. is desired in the

secondary coil, as the effect of this would be to magnetically screen the one from the other and so defeat the object in view. As a matter of fact, an apparatus of this description is used for medical purposes, and the E.M.F. induced in the secondary coil is regulated by inserting an iron tube between the coils, and thus screening them from one another to an amount depending on the E.M.F. required.

The iron must be laminated, as in the case of a dynamo armature core, to avoid as far as possible the generation of eddy currents due to the rapid changes in the number and direction ot the lines of force projected through the iron; and the metal employed must also have a low coercive force, to minimise the loss by hysteresis. Instead of a primary current which merely rises and falls in strength, an alternating current, such as that developed by any one of the alternators described in Chapter VIII., may with advantage be and usually is employed.

If the magnetic circuit be a good one, and the number of convolutions in the two coils equal, then by sending a rapidly alternating current through the primary, an alternating current of about the same strength and E.M.F. might be obtained in the secondary coil. Again, the secondary might consist of a great length of wire in many convolutions, thin wire being employed to enable it to be kept near to the primary. In this case the primary lines of force would cut the secondary circuit many times, and the induced E.M.F. would be much greater than that urging the current through the primary. But since the power obtained from the apparatus cannot be greater than or even equal to that given to it, a corresponding reduction in the other factor—that is, the current—would be observed; in other words, while the E.M.F. would be greatly increased, the current would be correspondingly feebler than that in the primary.

The student is probably familiar with a piece of apparatus known as an 'induction coil,' in which a rapidly interrupted heavy current of low E.M.F. is passed through a few turns of thick wire, adjacent to an enormous number of turns of finer wire. A bundle of thin varnished iron wires serves as a core, and a very feeble current of extremely high E.M.F. can be obtained in the secondary circuit. Such apparatus has proved of considerable

value in experimental researches; but we are far more concerned with the effects obtained by proceeding in the reverse order, viz. by making the length of the wire in the primary coil much greater than that in the secondary.

Supposing, for instance, we use the fine wire coil of an ordinary induction coil as the primary, and the thick wire coil as the secondary; the former has considerable resistance and self-induction, and it will require a high E.M.F. to send an alternating current of even feeble strength through it. But on measuring the resulting current in the thick wire coil (now being used as the secondary), it will be found that while the E.M.F. is low, the current passing through this low-resistance circuit is comparatively heavy. It is a most important fact that by constructing such an induction coil so that nearly all the primary lines of force can effectively cut the secondary, the secondary E.M.F. can be made to bear nearly the same ratio to the primary E.M.F. that the number of convolutions in the one coil bears to the number in the other. Therefore, by making the resistance of the magnetic circuit very low, as indicated above, and also making the electrical resistance of the secondary coil very low indeed, so that but little loss of power occurs in overcoming its resistance when a fairly heavy current flows, we can obtain at the terminals of the latter an alternating potential difference whose average value is, under all circumstances, practically equal to a definite fraction of the average of the alternating potential difference maintained at the primary terminals.

For instance, if the primary consists of 1000 turns and the secondary of 10, and a current of 1 ampere passes through the primary coil while the potential difference is 500 volts, then the secondary current may be 100 amperes, and the induced E.M.F. rather less than 5 volts. This is the important case with which we have to deal, for it thus becomes possible to effect the much-desired object of transmitting electrical power at a high electrical pressure, and employing it at the required point at a lower pressure. A piece of apparatus which is capable of effecting this transformation from high to low pressure is called a 'transformer.'

The first transformer was constructed in 1831 by Faraday. The principles which he then discovered, of the remarkable action of a varying current upon an adjacent circuit, are of almost inconceivable importance; while the method of constructing his original transformer, which we shall briefly describe, was well abreast of the then existing practice.

Faraday procured a welded ring of soft round bar iron, $\frac{7}{8}$ inch thick, the external diameter of the ring being 6 inches. Round one part of this ring he wound about 72 feet of copper wire, $\frac{1}{20}$ inch in diameter, in three superposed helices, the distance round the ring thus covered being about 9 inches. The wire was bare, the first helix being insulated from the iron by a layer of calico; and twine was wound side by side with the wire, to prevent contact between adjacent convolutions. Then followed another layer of calico, over which was wound the second helix, insulated with twine similarly to the first, then another layer of calico followed by the third helix, the whole being covered by calico. The ends of each helix were brought out so that the three coils could be used separately, or conjointly, in series or in parallel.

On the other half of the ring a length of 60 feet of copper wire was wound in two equal helices, and insulated in precisely the same manner as before. These two coils were joined in series to form the secondary circuit and connected to a galvanometer. The other three helices were also joined in series, to form the primary circuit, and a battery was connected up to them. The immediate effect of making this latter connection was seen in a violent deflection of the needle of the galvanometer placed in the secondary circuit. The needle quickly came to rest at zero, but was deflected momentarily in the opposite direction on the battery being disconnected from the primary circuit.

This result is precisely similar to that which we have described in connection with the apparatus depicted in fig. 281, but in this instance the lines of force of the current in the primary coil were, of course, conducted round by the iron ring through the secondary coil, and the sudden cutting of this latter coil by them gave rise to the observed currents. As might be expected, however, a great many of the lines of force did not reach the secondary coil, and Faraday obtained a more violent deflection

with the same primary current and shorter lengths of wire, by so arranging the two circuits that nearly all the lines of force generated were able to cut the secondary circuit. He disconnected the two helices which in the previous experiment were used as a secondary circuit, and in their place took two of the three superposed helices on the other half of the ring, joining them in series and to the galvanometer. The battery was then joined to the third helix, which formed the primary circuit, and although the lengths of wire were so much shorter, rather better effects were obtained, because of the increase in the percentage of the lines of force usefully employed; and, of course, since the resistance of the primary coil was diminished in the latter case, the primary current was correspondingly increased, the number of ampere turns remaining, however, nearly constant. Had Faraday supplied the primary circuit with a rapidly alternating current, he might have obtained an alternating current in the secondary circuit; but his galvanometer would not have indicated the presence of this current if the reversals were too rapid to give the needle time enough to move with each pulsation.

Advancing now to the consideration of a practical piece of apparatus based upon these principles, we may repeat that a transformer should be so designed that it can effect the required reduction from high to low pressure with as little waste as possible. The wires of the two circuits should be so disposed with respect to each other that the greatest possible number of the primary current's lines of force cut the secondary circuit, while if iron is employed to assist in this direction, care must be taken that but little energy is lost in it by eddies and hysteresis.

To reduce the loss by eddy currents the iron must be laminated at right angles to the path which they tend to take, while it must be left, as far as possible, continuous in the direction of the lines themselves. Loss by hysteresis increases with the rapidity with which the current alternates, and with the density of the lines of force through, and the mass of, the iron, as well as the coercive force of the iron employed. These points must receive due consideration when the rate of alternation and the mass of the iron in the core are being decided upon. The maximum number of lines of force per square centimetre is rarely

allowed to exceed 7000 in the case of a transformer core. Attention must also be devoted to such points as economy of construction, efficiency of insulation, and the facilities for the escape of the heat which is the evidence of the inevitable loss during the conversion.

Perhaps the simplest style of practical transformer is a slight modification of Faraday's original one. An iron core might be entirely overwound with a few layers of thick insulated copper wire to form the secondary circuit, and a number of layers of thinner wire then wound over this to form the primary. Resistance is of comparatively small importance in the primary coil, but it must be kept low in the other coil, because that carries a heavy current.

It might be thought that some advantage would be derived by interlacing the two coils so as to bring them into closer proximity, but this cannot be done in practice on account of the difficulty in maintaining effective insulation. The potential difference between even the extreme ends of the secondary coil is low, and little trouble is experienced in insulating this coil, but quite the reverse obtains with the primary. The wire-covering must not be too thick, otherwise the space occupied becomes great, but the utmost care must be taken to avoid bringing into proximity any convolutions separated from each other by a long length of wire, and therefore having a high potential difference between them. And as in practice wires connected to the secondary circuit are frequently led into places where they can be and are handled, every precaution must be taken to effectually insulate the secondary from the primary. For this reason the two coils are never interlaced, but are wound separately, with effective insulation between them.

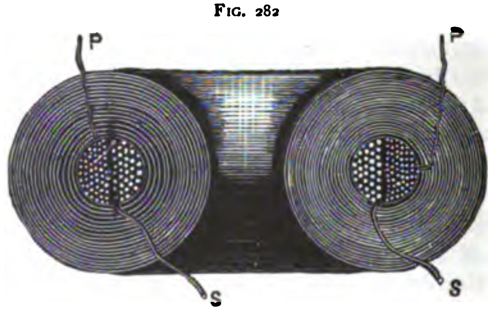
The simplest way of laminating the iron core of such a transformer is to build it up of thin iron wire, in exactly the same manner as the core of the original Gramme-ring armature. In fact, a Gramme-ring armature having a large number of convolutions can be readily turned into a very fair transformer, by using two or three equidistant sections joined in parallel for the secondary coil, and the remainder in series for the primary.

The rapid reversals of magnetisation which take place quickly heat the iron core, however well it is laminated. The heat must

escape, and when the iron is enveloped by copper, the heat must be imparted to the copper before it can reach the external air. This heating of the conductor is very undesirable, and for this and several other reasons it is preferable to place the iron outside instead of inside the coils, the position of the iron being quite immaterial, provided it can act effectively in leading the lines of force through the desired paths.

In fig. 282 is illustrated one method of constructing such a transformer. Its external appearance is that of a massive ring of small internal diameter, and in the figure is shown a section taken through a diameter, at right angles to the plane of the ring. The primary and secondary coils are each wound in a single coil, and lie close together concentrically. They are wrapped round with an insulating material, and over this is wound spirally an enormous quantity of soft iron wire. The inner coil of thick wire, S S, is the secondary, while the primary coil of thinner wire, P P, lies outside it, and it will be observed that the depth of the layer of iron wire is about equal to the diameter of the compound coil of copper wire. Such a transformer gives fairly good results, for nearly all the primary lines of force extend out to the massive iron-wire shell, and in so doing cut the secondary. But it is an extremely tedious and expensive piece of apparatus to make on a large scale, on account of the slow process of winding the enormous length of iron wire. Further, if a fault should occur (and faults *will* occur), it becomes necessary to remove the whole of the iron wire before the coils can be got at, to remedy the fault.

FIG. 282



Consequently large transformers are not made in the manner illustrated, although in most cases the principle is the same. The apparatus usually consists of two coils of wire, nearly oblong

in shape, lying side by side with an easily fixed and easily removable laminated-iron covering.

About fifty years ago a first-rate method of constructing a transformer was patented by C. F. Varley, which may be regarded as a combination of the two types mentioned. He took a bundle of iron wires of approximately equal lengths and over this bundle wound the primary and secondary coils. These coils were placed in the middle of the bundle, and extended along it for a distance equal to one-third of its length, so that the iron wires protruded from each end to a distance equal to the length of the coils. The ends of the iron wires were then bent round over the outside of the coils, so as to meet and overlap each other, thus completely encasing the coils with iron, except at one place through which the connecting wires were led.

But the necessity for large transformers did not then exist, and the method was scarcely at all employed.

The magnetic circuit of modern transformers is built up of a number of flat plates of sheet iron, placed so that the plane of the sheet may be as far as possible parallel to the direction in which the lines of force are thrust through the iron. They are usually insulated by a thin coating of varnish, or by paper, or sometimes calico, and the devices by which such plates may be cheaply made and placed in position are very numerous. As they differ but little in principle, we need select only the following examples for description.

Fig. 283 is a sectional view of the Brush Company's standard single-phase transformer, which is completely enclosed in the iron frame, and designed for use in the sub-station of a public supply system. The primary and secondary coils are wound one over the other on the two vertical limbs of the iron core of the transformer. In fig. 284 a perspective view of this core is given, from which it is seen that the plates of thin iron, 0·014 in. thick, are clamped and bolted together by means of massive castings. The iron is of a quality specially selected for its non-ageing properties—that is to say, it is capable of maintaining its freedom to respond to rapid reversals of the magnetic field for a considerable time. It has been noticed that some classes of iron when subjected for a long time to rapid reversals 'age' or 'fatigue,' or,

in simple language, show a tendency to respond less freely to reversals in the direction of magnetisation, the particles of iron being increasingly difficult to move, and as a consequence the hysteresis losses increase.

The secondary (or low-voltage coil) is placed next to the core, from which it is insulated by a special tube of insulation. Another tube of insulation is then slipped over the secondary winding, and then the primary coils are placed in position. Since

FIG. 283

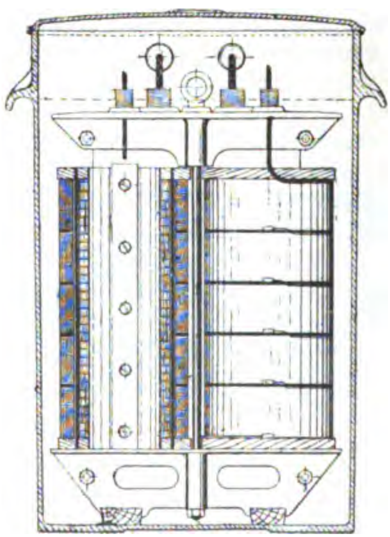
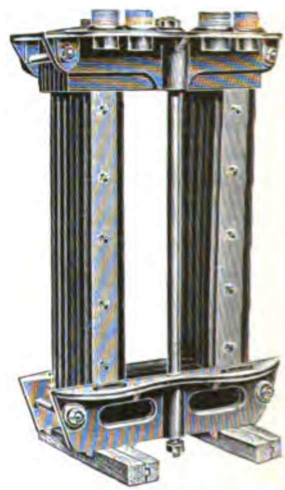


FIG. 284



the primary winding is subjected to high pressure it is wound in sections, and each section is separately taped with oiled linen, and by this means the danger of a breakdown is minimised, and even if a breakdown does occur the faulty coil can be removed and a new one replaced without much trouble. The coils are composed of cotton-covered wires wound on formers insulated and baked in a vacuum oven to dry out all the moisture.

In fig. 285 two views of a three-phase transformer are shown, the construction being similar to that of a single-phase transformer,

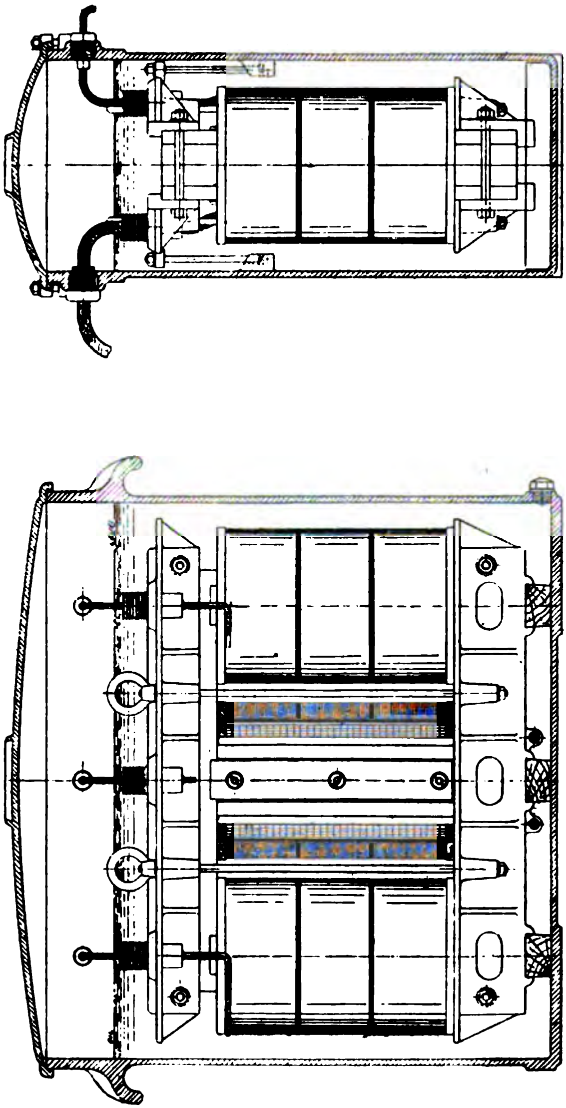


FIG. 285

excepting that in the former case three cores are used to wind the coils on instead of two. The whole of the core and windings are immersed in oil in order that the cooling may be efficient. The temperature rise of the transformer after a continuous run at full load does not exceed 90° F. when this method of cooling is adopted. The cast-iron box containing the transformer is provided with a cover which is bolted to the box, and the oil can be emptied out when required by means of the screw plug shown in the lower right-hand corner of the longitudinal view. Flexible leads connected to the coils are brought out through glands in the box. The standard primary voltage for which the transformers are constructed is 2000 volts, but this can, of course, be easily increased, and transformers can be wound for any desired voltage and any desired ratio of transformation.

Fig. 286

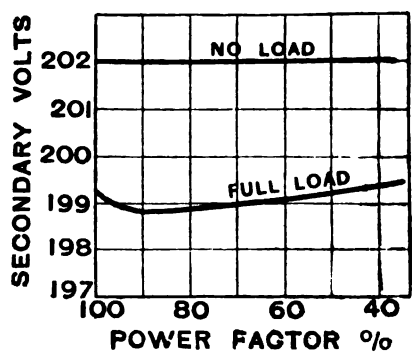
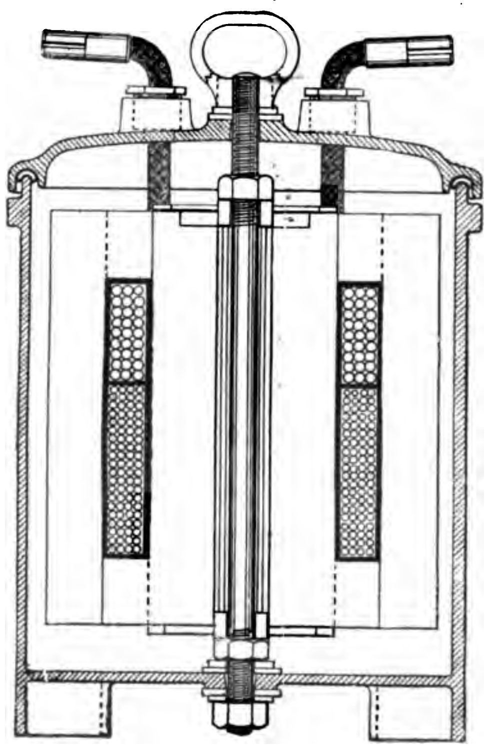


Fig. 286 is interesting. It shows the variation in pressure at the secondary terminals, under varying 'power factors,' for a 40-kilowatt transformer. With the secondary terminals disconnected a potential difference of 202 volts is maintained. At the full-load current, and with the maximum power factor, such as would result when the secondary coil is joined to a group of incandescent lamps or any other similar inductionless load, the pressure is 199·2 volts, and through the whole range the drop in voltage is less than 1·5 per cent.

Small transformers for loads up to 3 kilowatts are specially constructed for house-to-house supply or for alternate-current arc-lamps. The coils are wound over a circular iron core, consisting of sheet-iron stampings about 0·014 in. thick, the magnetic circuit being completed by means of L-shaped stampings, which are placed in position after the coils have been wound on. A sectional view of one of the arc-lamp transformers is given in fig. 287. It

will be seen that the primary and secondary coils are wound side by side, and that the space occupied by the iron is proportionally large. When the transformer is intended for reducing the pressure to 35 volts for a single arc-lamp, the reactance (see p. 592) is increased by the method of construction, so that a separate choking

FIG. 287

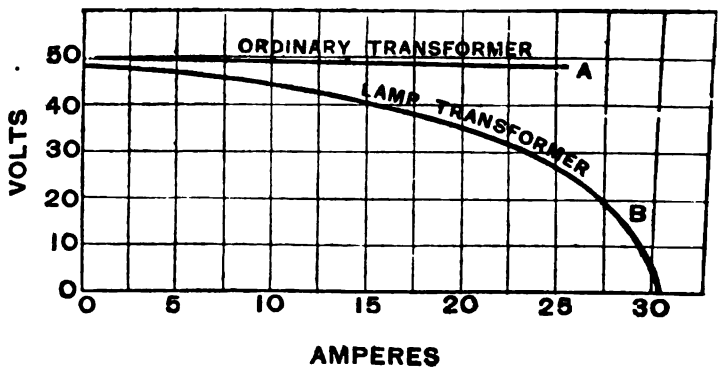


coil which would otherwise be necessary can be dispensed with. The effect of this is illustrated in fig. 288, which gives two characteristic curves; A for a small ordinary transformer, and B for a self-choking arc-lamp transformer. It will be seen that in the former case the voltage remains almost constant as the current is increased, while in the latter an abnormal rise in the current

is accompanied by a rapid fall in the voltage. If it were not for this or some similar provision, a partial short-circuiting of the lamp might be followed by disastrous results—that is to say, the lamp would either be burned up or the protecting fuse melted.

Transformers have been put to an interesting use for the purpose of obtaining the very heavy currents which are necessary in electric welding. The method consists in placing the two pieces of metal required to be welded end to end, and subjecting them to moderate pressure against each other. A very heavy current is then passed from one to the other, and as they make imperfect contact at their opposing surfaces, considerable resist-

FIG. 288



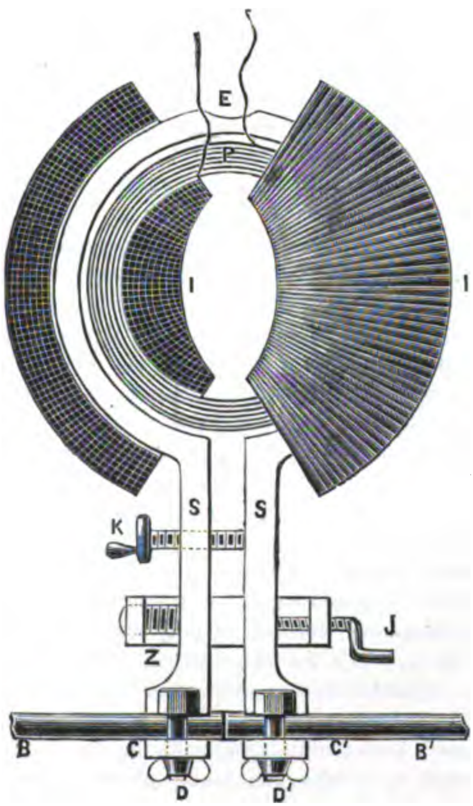
ance is there offered to the passage of the current, and a very intense heat is consequently developed at the point where it is required to make the weld. If the current is sufficiently strong, the opposing surfaces get white hot, and being pressed together they unite perfectly, bulging out, however, round the edges. It is necessary that the surfaces should be perfectly clean, and a flux, the composition of which depends upon the nature of the metals to be welded, is usually employed to prevent the oxidation of the surfaces and so render the weld more perfect. In the case of iron, a little borax is sprinkled over the ends of the rods.

But in order to sufficiently raise the temperature of thick rods of metal, enormous currents are required; for instance, a current

of about 20,000 amperes would be required to weld a steel rod seven-eighths of an inch thick. In such a case the resistance of the current generator must be extremely small, otherwise the power absorbed in it would amount to many horse-power.

Secondary batteries might be employed for the smaller currents, but the most economical method is to generate an alternating current by means of a dynamo, at a fairly high E.M.F., and, reducing this to a considerably lower E.M.F. by means of a transformer, obtain at the same time an increase in the current strength.

FIG. 289



Various types of transformer have been employed for the purpose, one form being illustrated by the diagram in fig. 289. The primary coil, P, is composed of a number of turns of wire, wound in a circular coil; the secondary consists of a single massive copper strip, S S, bent into a circular form, and placed concentrically with the primary coil. Over the two coils is wound a quantity of iron wire, I I, in two masses, space being left between them on one side for the passage of the wires leading to the primary coil, and on the other side, to bring out

the massive straight bars forming the ends of the secondary coil. The bars can be held open by means of the screw at K; their extremities being provided with massive clamps, C C′, in which the pieces to be welded, B B′, are fixed. A spiral spring at I presses the ends together, the pressure being regulated by means of the screw at J. There are several modifications of this apparatus for performing special classes of work, the principle, however, being in nearly all cases the one illustrated. More elaborate mechanical contrivances are frequently introduced for clamping the rods or tubes to be welded, and for regulating the pressure at the junction.

When the source of supply is on the direct-current system a rotary converter is employed to convert it into an alternating current, and this current is then passed through a transformer in order to obtain a current of the required strength.

For ordinary work a current of 12,000 amperes is the maximum required, and in such a case the power is usually supplied to the primary at an E.M.F. of about 600 volts, the current being 20 amperes. A certain amount of this power is, of course, lost during the conversion; but a current of 12,000 amperes at an E.M.F. of nearly one volt can be obtained in the secondary circuit.

It is important to observe the reason for most of the heat being developed at the proper point. When the current is started in the secondary circuit, the resistance at the junction is far greater than the resistance of the whole of the remainder of the circuit; consequently the fall of potential there is comparatively great—that is, nearly the whole of the power appearing in the secondary is expended in overcoming the resistance at the opposing surfaces. These surfaces get hot, and being pressed together, they make much better contact immediately the rise in temperature is sufficient to render the metal plastic. The rise in temperature, however, considerably increases the resistance of the metal itself, and consequently the expenditure of power at this point is still proportionally great. The ease with which the heat can be confined to any particular locality constitutes one great advantage of the electrical method. The clamps make contact with a large surface, to avoid, as far as possible, the introduction of resistance,

and they are so designed that the removal of the welded rods can be speedily effected.

Before proceeding with a further consideration of the manner in which transformers can be employed, it will be advisable to briefly discuss some of the peculiarities of alternating currents. Hitherto when comparing alternating currents with direct currents, we have considered only the simple average value of the former. But it is important to note that in cases where it is required to compare alternating and direct currents with respect to their capabilities for performing work, this simple average value of an alternating current does not enable us to directly effect the comparison. For example, if a current varies according to the sine law, its average value is 0·637 of its maximum value—that is to say, if its maximum strength is 1 ampere, its average strength is 0·637 ampere. But if a steady current of 0·637 ampere is maintained through an incandescent lamp, the lamp is less brilliantly lighted than by an alternating current whose maximum reaches 1 ampere, and whose average value is therefore 0·637 ampere, which clearly shows that more work is being done by the alternating than by the direct current. This arises from the fact that the work performed at any instant varies as the *square* of the current strength at that instant, and the average of the square of the current at every instant is greater than the square of its average value. In fact, in the case of a current varying according to the sine law, and with a maximum value of 1 ampere, if the current strength at every instant be squared, the average value of these squares will be 0·5, the square root of which is 0·707. Consequently such a current is equivalent, as regards heating-power or the performance of other work, to a steady current of 0·707 ampere. Precisely the same argument applies with respect to electro-motive force, and to avoid misunderstanding it is usual to refer to this 'square root of the mean square' value of an alternating current or pressure as the 'virtual' amperes or volts, as the case may be.

It may be noted, for example, that a Siemens dynamometer indicates virtual amperes, since the force of attraction is at any moment proportional to the square of the current strength; while for a similar reason an electrostatic voltmeter indicates virtual

volts. Similarly, a hot-wire voltmeter indicates virtual volts, because the heat developed in the wire is at every instant proportional to the square of the current strength, and this square varies with the square of the pressure.

It must be distinctly understood that the work which can be done by an alternating current is proportional to 0·707 of its maximum value when the current curve is a sine curve such as that depicted in fig. 143, and that it may have a greater or less value in other cases depending upon the shape of the curve; and the same remark applies to the electro-motive force. Many alternators which have no iron in their armatures give an E.M.F. curve which is almost exactly a sine curve, but the resulting current does not necessarily rise and fall even approximately according to the sine law, unless the circuit is devoid of coils with iron cores. But whatever may be the shape of the curve, the 'virtual' value is found, as stated above, by taking the square root of the sum of the squares of the values at every instant during a complete cycle.

We know that when a steady E.M.F. is applied to the extremities of any conductor, a steady current always flowing in the same direction is obtained; and after the first instant the presence or absence of self-induction in the circuit makes no difference in the current strength. In such a simple case the power expended is at once obtained by multiplying the current by the E.M.F., because both quantities are constant in value and the current always flows in one direction—namely, that in which the E.M.F. is acting. When, however, the E.M.F. varies in strength or alternates in direction, the calculation of the power expended cannot be so easily made. The simplest case occurs when the circuit contains no self-induction, because then the current instantaneously changes with every change in the E.M.F., rising and falling with it and giving a curve of exactly the same shape. The power being expended at any instant is then equal to the volts multiplied by the amperes at that instant; and therefore the product of virtual volts and virtual amperes will always give the correct value of the power expended in any circuit having no appreciable self-induction, such as, for example, an incandescent lamp.

When, however, the circuit contains self-induction, the current does not rise and fall simultaneously with the E.M.F., but lags

behind it, the amount of the lag depending upon the value of the self-induction—that is to say, the maximum value of the current strength occurs later than the maximum E.M.F., and the direction of the current is not reversed until after the E.M.F. has been reversed and is acting in the opposite direction. It therefore follows that twice during each alternation or complete cycle the current is flowing in a direction opposite to that in which the E.M.F. is acting, and we must consider how this state of affairs affects the expenditure of power in the circuit. A mechanical analogue may here prove of some assistance, and from the numerous examples which readily suggest themselves we may, perhaps, select a heavy pendulum, which, being kept swinging, can be considered as representing an alternating current, the force which has to be applied to keep the pendulum in motion being equivalent to the electro-motive force. In order to more nearly represent the state of affairs in a circuit having no self-induction, the pendulum should be so balanced that it will remain at rest in any position; and it may then be kept swinging by pressing in alternate directions against a small rigid rod fixed at right angles to the direction of motion. The pressure exerted will then always be in the same direction as the motion, and work will always be performed at every stage. But if the pendulum be unbalanced and allowed to swing freely, and the rigid rod be replaced by a flat steel spring, the case of a circuit having self-induction may be approximately represented. Work is actually expended during the whole time that the pendulum is moving in the same direction that the pressure is applied to the spring, but by endeavouring to make the pendulum swing faster than its natural rate it will be seen that the pressure must be reversed each time before the pendulum has come to the end of its journey, and then as its inertia still carries it forward against the pressure it bends the spring and so stores up energy which is again given out by the spring when the pendulum begins to move back again. This analogy is imperfect, but it will serve to bring out the point that twice during each complete oscillation or cycle when the pressure is in opposition to the motion, work is stored up to be given out again instead of being expended, and due allowance must be made for this in estimating the total amount of energy expended; and

it will be evident that the more the motion lags behind the pressure the greater becomes the amount which must be allowed. In just the same way, when the current lags behind the E.M.F. in an inductive circuit, due allowance must be made for those periods during which the current and E.M.F. are opposite in direction, energy being stored up and given out again by the collapsing lines of force in somewhat the same manner that it is stored up and again given out by a bent spring. The power may still be estimated as before by multiplying the virtual volts and amperes if due attention be paid to the direction by introducing algebraic signs. Thus if E and C represent respectively the virtual volts and amperes during the time that both E.M.F. and current are in the same direction, and e and c the virtual volts and amperes while the current is flowing in opposition to the E.M.F., the power expended will be

$$\mathrm{E} \times \mathrm{C} + (e \times -c) = \mathrm{E\,C} - e\,c \text{ watts.}$$

In some cases, however, it is possible to determine the exact extent to which the current lags behind the E.M.F., and the lag may be conveniently expressed in degrees, since, as we have seen, a complete cycle is represented by 360° and the value of the lag so expressed is known as the 'angle of lag.' In any inductive circuit when the curves are sine curves the power expended is equal to the product of virtual volts and virtual amperes, multiplied by the cosine of the angle of lag, and the proportion which this value bears to the product of amperes and volts in an inductionless circuit is known as the power factor.

For instance, if the angle of lag were 10° (the cosine of which is 0·985) and the virtual amperes and volts 10 and 50 respectively, the power expended would be $10 \times 50 \times 0{\cdot}985 = 492{\cdot}5$ watts, and the power factor would be 0·985 or 98·5 per cent. In the extreme case, which cannot be easily attained in practice where the current lags 90° behind the electro-motive force (in which case they would be said to be 'in quadrature') no power would be expended in the circuit, because the cosine of 90° is 0. This ideal state of affairs would result from the fact that the current and pressure would be in opposite directions during precisely the same length of time that they were in the same direction, and just as much work

would be returned by the inductive circuit in the one interval as would be expended in the other interval.

Since the lag of current behind the E.M.F. depends so largely upon the value of the self-induction of the circuit, it becomes important to examine more closely the conditions which determine the self-inductive effect. We have already seen, in Chapter VII., that when a long straight length of wire is wound into a coil of many convolutions, its resistance remains unaltered, but another property is introduced which only becomes evident when the current is changing in value and which is due to the lines of force in springing out from or collapsing upon any one convolution cutting some or perhaps all of the other convolutions. The effect of this self-induction is to retard the rise or fall of the current in the coil, and consequently if such a coil be placed in any circuit in which there is an alternating E.M.F. the resulting current strength will be less than if the wire were straightened out so that only the resistance had to be dealt with. If there is no iron inside or in the vicinity of the coil, the matter is somewhat simplified, and the total self-inductive effect or 'inductance' may be estimated by the number of those lines of force which springing out from and collapsing upon the various convolutions cut the other convolutions of the coil; this number will depend upon the current strength, but also upon another factor which depends upon the number of convolutions in the coil and their disposition, that is upon the shape of the coil; this latter factor is termed the 'coefficient of self-induction' of the coil, and it may be measured in terms of a unit called the *henry*. If a current be started in the coil, the self-inductive effect will generate a counter or back E.M.F., proportional at any instant to the rate at which the current is changing in strength; and if when the current is made to rise uniformly during one second from zero to one ampere the back E.M.F. during that second is one volt, then the coefficient of self-induction of the coil is one henry. The coefficient of self-induction of a coil is generally denoted by the symbol L, and it is constant in value for a coil without iron. The total number of lines of force interlinked in the coil varies with C, the current strength at any instant, and is equal to the product of L and C. The E.M.F. induced in the coil when the current varies is equal to L multiplied by the rate at

secondary lines of force assist the reversal of the primary current. This reaction is greatest when most needed—that is, when the secondary circuit resistance is least—because then the secondary current is greatest, and it causes the transformer to be automatically self-regulating, taking up power in the primary coil as demanded by the conditions existing at the moment in the secondary circuit. It will be seen that so far as the eddy currents are concerned the iron core may be treated as a subsidiary secondary coil, and it will then be easy to understand how the power lost in eddy currents is taken up by the primary, because these currents react to increase the primary current and reduce the lag in just the same way as the secondary current does.

The primary impressed E.M.F. is of course the actual cause of the results obtained with a transformer, but there are some advantages in starting with a consideration of the magnetisation changes in the iron core and in work [illegible] wards to the impressed E.M.F. and forwards to the seconda[illegible] The magnetisation of the core is continually reversed[illegible]ay, it periodically oscillates between a positive maxi[illegible]gative maximum and under all conditions both th[illegible] the secondary coils embrace and are being cut by t[illegible]er of lines of force. This cutting produces an E.M.F. [illegible]proportional in value to the number o[illegible]tions [illegible] The secondary E.M.F. is low becaus[illegible] convo[illegible]condary coil; the primary induce[illegible]her ar[illegible]ortion to the ratio of the convo[illegible]rimar[illegible]ith the secondary coil. Both [illegible]ced [illegible] same direction or in the sa[illegible] the [illegible] E.M.F. is that known as the co[illegible] necessarily in opposition to the [illegible] the secondary load is inductionless [illegible] lamps, the secondary current, second[illegible] E.M.F. will be similar in phase and all 90 [illegible] This latter result follows from the fact tha[illegible] is highest (either positive or negative) the [illegible] an instant zero, and the induced E.M.F.'s also [illegible] of change and the induced E.M.F.'s are at a ma[illegible] the reversal in direction of the lines of force [illegible]

The primary back E.M.F. is opposite in direction to, but slightly behind, the impressed E.M.F. by which it is generated; consequently the secondary E.M.F. is almost exactly opposite in phase to the primary impressed E.M.F. The primary current lags behind the impressed E.M.F., to a varying extent depending, as has been shown, upon the secondary current.

The magnetisation of the iron core is practically the same at all loads, and therefore the eddy currents and iron losses are practically constant; the losses by heating the coils vary with the square of the current strength therein.

On account of the excellent regulating properties of good transformers when worked on the parallel system, this system is generally adopted, and we need not consider the practically extinct series system.

We may distinguish two separate systems of running transformers in parallel. The first, known as the distributed transformer system, is the more suitable when current has to be supplied
numb separate buildings which are situated at some
ce o he other, and in such a case the high-pressure
re e whole district and led into each building
to a separate transformer which supplies
econd, or sub-station system, the high-
into the premises to which current is
number of sub-stations are arranged
veral transformers may be placed,
ins can then be taken from the
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cost for a given output;
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loss of pressure in
load, and unless
om the supply

to reduce the secondary E.M.F.; (3) the losses by eddy currents and hysteresis should be reduced as much as possible by methods which have already been fully explained; (4) the resistance of the secondary coil should be as low as possible in order that the fall of potential therein with the maximum current may be inappreciable.

We will consider the two extreme cases—first, when the secondary circuit is disconnected and the load therefore *nil*; secondly, when the secondary load is heaviest, which is the case when the resistance of the secondary circuit has its lowest value. In the first case when the secondary circuit is disconnected the secondary coil has practically no effect and may be considered as nonexistent. The transformer may be treated as if it consisted of the primary coil and iron core only, and as this coil has many convolutions and is surrounded by a good magnetic circuit, its coefficient of self-induction is extremely high, and the total self-induction effect or reactance will also be very great because the impressed E.M.F. alternates rapidly. Consequently, although the resistance of the coil may be fairly low, the impedance is great and the current strength will be small, in spite of the fact that the impressed E.M.F. may be, say, 2000 volts. The power expended, as measured by E × C, might, however, still be considerable, since E has such a high value, but we know that in order to get the true value of the power this product must be multiplied by some such quantity as the cosine of the angle of lag, and as in a good transformer the angle of lag will under these conditions be nearly 90°, this latter factor reduces the value of the power expended to a very small value. It is not practicable to treat this part of the subject algebraically without assuming conditions which do not exist in practice (for example, true sine curves and iron cores of constant permeability), but it will be readily understood that the total power expended on the transformer when the secondary circuit is open is made up of two parts: (*a*) the heat generated by the current in the primary coil conductor; (*b*) the losses by heating the iron core. It is important to keep these losses low, because a transformer is generally on 'open circuit' during the greater part of the twenty-four hours. The first-mentioned loss (*a*) can be calculated as the product of ohms and virtual amperes squared, both of which factors should, as we have seen,

be fairly low, while the second (*b*) is made up of eddy current and hysteresis losses.

The fact that the current is small when the self-induction of the primary coil is high will be evident when we remember that if, as is frequently the case, the rate of alternation is 50 per second, the E.M.F. will only be applied to the primary coil in one direction during $\frac{1}{100}$th part of a second, and in order to produce the flux corresponding to the E.M.F. applied to the primary terminals, only a very small current is required, in fact only sufficient current to magnetise the iron.

These considerations explain how it is possible to leave a transformer on open secondary circuit permanently joined up to the high-pressure mains without incurring a continual heavy loss, and it now remains to explain how more power can be taken up and transferred to the secondary circuit when required; for example, when the maximum number of lamps is connected in parallel across the secondary terminals. While the secondary circuit was open a definite alternating potential difference was maintained at the terminals of the secondary coil, and this might readily have been indicated and measured, without disturbing the conditions, by means of an electrostatic voltmeter. When the secondary circuit is completed this potential difference causes a current to flow, and if the resistance of the secondary coil is negligibly small this current will be inversely proportional to the resistance of the external secondary circuit. It is the reactive effect of this secondary current which enables the primary coil to take up more power from the mains, first by increasing the primary current, and secondly by reducing the angle of lag between the E.M.F. and current, and the power thus taken up would in a perfect transformer be inversely proportional to the resistance of the secondary circuit. In order to more clearly understand the effect of this reaction the student may with advantage again read that portion of Chapter VII. dealing with the mutual induction between two coils. It will be seen that when the current starts in the secondary coil its lines of force in springing out to pass through the iron core must cut the primary coil convolutions, and the E.M.F. thus set up is in such a direction as to assist the primary E.M.F. in increasing the primary current; and conversely, the collapsing

secondary lines of force assist the reversal of the primary current. This reaction is greatest when most needed—that is, when the secondary circuit resistance is least—because then the secondary current is greatest, and it causes the transformer to be automatically self-regulating, taking up power in the primary coil as demanded by the conditions existing at the moment in the secondary circuit. It will be seen that so far as the eddy currents are concerned the iron core may be treated as a subsidiary secondary coil, and it will then be easy to understand how the power lost in eddy currents is taken up by the primary, because these currents react to increase the primary current and reduce the lag in just the same way as the secondary current does.

The primary impressed E.M.F. is of course the actual cause of the results obtained with a transformer, but there are some advantages in starting with a consideration of the magnetisation changes in the iron core and in working backwards to the impressed E.M.F. and forwards to the secondary current. The magnetisation of the core is continually reversed—that is to say, it periodically oscillates between a positive maximum and a negative maximum and under all conditions both the primary and the secondary coils embrace and are being cut by the same number of lines of force. This cutting produces an E.M.F. in each coil proportional in value to the number of convolutions of the coil. The secondary E.M.F. is low because of the few convolutions in the secondary coil; the primary induced E.M.F. is higher and in exact proportion to the ratio of the convolutions in the primary as compared with the secondary coil. Both of these induced E.M.F.'s are in the same direction or in the same phase, and the primary induced E.M.F. is that known as the counter or back E.M.F. and which is necessarily in opposition to the impressed E.M.F. If, therefore, the secondary load is inductionless as in the case of incandescent lamps, the secondary current, secondary E.M.F. and primary back E.M.F. will be similar in phase and all 90° behind the magnetisation. This latter result follows from the fact that when the magnetisation is highest (either positive or negative) the rate of change is for an instant zero, and the induced E.M.F.'s also zero; while the rate of change and the induced E.M.F.'s are at a maximum just when the reversal in direction of the lines of force is taking place.

The primary back E.M.F. is opposite in direction to, but slightly behind, the impressed E.M.F. by which it is generated; consequently the secondary E.M.F. is almost exactly opposite in phase to the primary impressed E.M.F. The primary current lags behind the impressed E.M.F., to a varying extent depending, as has been shown, upon the secondary current.

The magnetisation of the iron core is practically the same at all loads, and therefore the eddy currents and iron losses are practically constant; the losses by heating the coils vary with the square of the current strength therein.

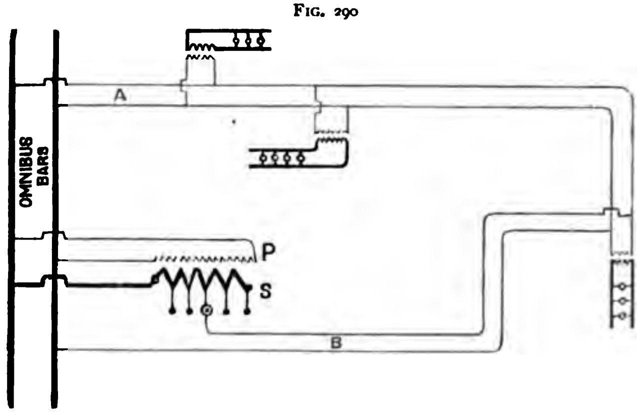
On account of the excellent regulating properties of good transformers when worked on the parallel system, this system is generally adopted, and we need not consider the practically extinct series system.

We may distinguish two separate systems of running transformers in parallel. The first, known as the distributed transformer system, is the more suitable when current has to be supplied to a number of separate buildings which are situated at some distance one from the other, and in such a case the high-pressure mains are run over the whole district and led into each building and there connected to a separate transformer which supplies that building. In the second, or sub-station system, the high-pressure wires are not led into the premises to which current is to be supplied, but a small number of sub-stations are arranged at suitable points, in which several transformers may be placed, and a low-pressure system of mains can then be taken from the sub-station to supply the buildings in the neighbourhood. This latter system is only economical when a considerable amount of power is required in the immediate neighbourhood of each sub-station, but it has the advantages that high-pressure wires need not be taken into the consumers' premises; large transformers may be employed, thus reducing first cost for a given output; and during periods of light load the greater number of these transformers may be switched out of circuit, thus reducing the iron- and copper-resistance losses.

Whichever system may be adopted, the loss of pressure in the primary mains becomes considerable at full load, and unless this is compensated for, the lamps at a distance from the supply

station become dim at full load if those near the station are supplied with the proper voltage. With a view to enabling a uniform pressure to be maintained, it is the practice, instead of supplying the whole of the power from the generating station by one pair of mains only, to form the high-pressure mains connected to the transformers into a kind of network, and to feed this network at selected points by pairs of mains termed 'feeders' which are connected to the omnibus bars at the generating station. It is manifest that the longer feeders must be supplied at the station end with a higher pressure than the shorter ones, and there are several methods of obtaining this regulation. The most

FIG. 290



obvious, but at the same time the most uneconomical, method is to maintain the omnibus bars at the pressure required by the longest feeder and reduce the pressure in the shorter feeders by the insertion of resistances, or, better still, 'choking' coils. It is evident, however, that a better method would be to maintain the omnibus bars at the pressure required by the shorter feeder and by some means increase the pressure in the longer feeders, especially if this increase can be varied to suit the variations of the load. Perhaps the best device for accomplishing this is that known as the Stillwell Regulator, the principle of which will be understood from fig. 290. Here A represents a pair of feeders supplying

the network at a point near the station, and B another pair supplying a more distant point; the regulator is placed in the circuit of the latter to raise the pressure therein sufficiently to compensate for the loss, and to maintain the pressure at, say, 2000 volts at the distant end of the feeder. The apparatus consists of a transformer whose primary coil P is connected to the omnibus bars, and whose secondary coil S is joined in series with one of the feeder conductors. The secondary coil is divided into a number of sections (five are shown in the diagram), and, by means of a suitable switching arrangement devised to minimise sparking, any number of sections may be thrown into circuit. In the present instance three sections are shown in circuit, and if the E.M.F. of the whole secondary coil is 100 volts, these three sections would add 60 volts to the feeder pressure. It is obvious that the increased pressure thus obtained can be varied to suit the load, and the required variation can be estimated from the indications of an ammeter placed in the feeder circuit or by any one of several other ingenious devices.

'Choking coils,' to which reference has several times been made, are simply coils of wire provided with iron cores to give them considerable self-induction. They are frequently placed in an alternating current circuit for the purpose of reducing the current strength therein, or in order to cause a certain reduction in the pressure between two points. Either result might be attained by the use of an ordinary resistance coil, as in the case of a continuous current, but a great advantage attending the use of a choking coil is that less energy is expended in producing the desired effect, because, as the coil is designed to have very great self-induction, the current is throttled or choked back, and instead of all the energy being expended in heating the conductor (as would happen with an ordinary resistance coil) the greater part is given back in the same way that the primary coil of a transformer returns power to the primary circuit. The iron core may be in any form—either a straight core embraced by the coil, or a number of sheet-iron stampings embracing the coil; the usual methods should be adopted to reduce the losses by eddy currents and hysteresis, and the resistance of the coil should be kept fairly low in order to keep down the loss in heating the conductor, and

in this way the desired result may be attained with but little expenditure of energy.

It is frequently necessary to have some means of varying the self-inductive effect of such a choking coil, and this may readily be done in either of two ways. The first is by varying the magnetic resistance of the magnetic circuit, and this method is most conveniently adopted when the core consists of a bundle of straight iron wires passing through the coil. It will be evident that, by withdrawing the core from the coil to a greater or less extent, the self-inductive effect can be varied within wide limits. A similar result can be obtained when the core forms a complete magnetic circuit by making one portion of it movable. The second method consists in the provision of a kind of secondary circuit in the shape of, say, a cylinder of copper which can be made to slide over the coil and core to a greater or less extent. The currents induced in this secondary circuit reduce the self-inductive effect exactly in the same way as does the current in the secondary coil of a transformer, and the choking coil is thus most effective when the copper cylinder is placed out of action, and least effective when it completely embraces the coil.

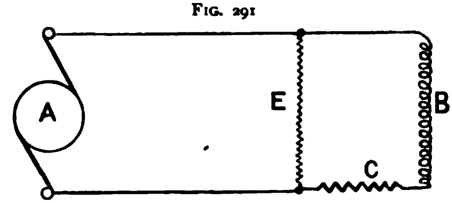
A choking coil is sometimes employed in connection with direct currents. In such cases the coil must be wound to the proper resistance to absorb all the necessary power by heating the conductor, and the advantage resulting from the self-inductive effect is only obtained at the moment of completing the circuit, when it prevents a sudden rush of current taking place. This point is of some importance in connection with the resistance coils which are frequently used in series with arc lamps, as will be presently described.

Many methods have been proposed for the measurement of the power absorbed in a circuit containing self-induction, such as the primary coil of a transformer, but few of them are satisfactory. Perhaps the best method is by means of a 'wattmeter.'

A wattmeter, as its name implies, is a piece of apparatus which when suitably calibrated indicates directly the power expended in any circuit or part thereof. Most of these instruments are based upon the Siemens dynamometer, which it will be remembered has two coils, one fixed and the other movable, through

which the current to be measured is generally passed in series. It was pointed out when describing this instrument that a separate and distinct current might be caused to flow through each of the coils, and although the currents need not be equal in strength, the turning effort on the movable coil would be proportional to the product of those two currents. Confining ourselves for the moment to direct currents only, we may suppose one coil to be joined in series with, say, the lamps fed by a direct-current dynamo, and the other coil connected across the terminals of the dynamo. The former coil would then carry the total current C supplied to the external circuit, and the current through the latter coil would be directly proportional to E, the difference of potential at the dynamo terminals. It is evident that the turning effect on the movable coil would be proportional to E × C—that is to say, to the total number of watts being expended in the circuit at the moment—and by suitable calibration the watts could be directly indicated by the instrument. If used for such a purpose the pressure coil, that is the coil connected across the dynamo terminals, would have to be wound with fine wire in order that the resistance offered might be sufficient to prevent the pressure being altered by placing the instrument in circuit, while the other or series coil should have a very low resistance to prevent any change being made in the current strength in the main circuit.

FIG. 291



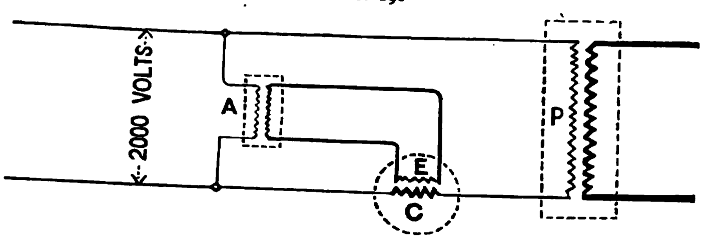
Now such a wattmeter may, with suitable precautions, be employed to measure the power taken up by, say, a choking coil or the primary coil of a transformer when supplied with an alternating current. In fig. 291, B represents a coil with considerable self-induction supplied with current from an alternator A, and it will be evident that if the fine wire or pressure coil E of the wattmeter be joined across the mains as shown, the current therein will be proportional to the pressure, while the series coil C being placed in the main circuit will take all the current supplied to the coil B. Further, the current in the coil B lags behind the

impressed E.M.F. on account of the self-induction of that coil, and the current will similarly lag through the series coil of the wattmeter. If, therefore, we can prevent any such lag in the pressure coil of the wattmeter, the current in this coil will keep in step with the E.M.F., and the turning effect on the movable coil will be reduced by an amount depending upon the lag of the main current behind the impressed E.M.F. The instrument can thus be made to indicate the true power taken up by the coil B. In the special case, therefore, when pressure and current are in quadrature, the wattmeter should indicate zero. This will be evident from a consideration of the fact that when the current in one coil lags 90° behind that in the other, the movable coil will receive four brief impulses during each alternation, and as these impulses alternate in direction and are of too brief duration to separately affect the coil, the coil will remain at rest. When the two currents are in step with each other the coil receives two impulses in each alternation, both in the same direction.

The wattmeter can be made without any iron and without any metallic fittings in which eddy currents may be induced; but it is evident that if the pressure coil consists of many convolutions of fine wire its self-induction will still be considerable, and the current therein will not be strictly in phase with the impressed E.M.F. This difficulty may be surmounted by making the pressure coil a few convolutions, and inserting in series with it a high non-inductive resistance. If, however, the E.M.F. were, say, 2000 volts, such as is frequently applied to the primary coil of a transformer, the value of this non-inductive resistance would have to be made very high, and then, in addition to the expense and inconvenience of working with such a high pressure direct on to the instrument, the power wasted would be considerable, because a fairly strong current must be made to flow through the pressure coil in order to obtain the requisite turning effect even for low readings. In such a case the proposal made by Dr. Fleming, to feed the pressure coil from the secondary circuit of a small subsidiary transformer, is a good way out of the difficulty. This arrangement of the apparatus is shown in fig. 292, where P represents the primary coil of the transformer whose power absorption it is desired to measure, C the series or current coil of the wattmeter,

and E the pressure coil; the latter is connected direct to the secondary coil of the small auxiliary transformer A, whose primary coil is joined across the mains. Since the load on this auxiliary transformer will always be light, the secondary E.M.F. will always be practically in step with the impressed E.M.F., although opposite in phase, and the wattmeter will still indicate the lag of current behind the impressed E.M.F. But it would obviously be difficult to calculate without considerable risk of error the exact fraction of the main circuit voltage which is now applied to the wattmeter pressure coil. All such difficulties are overcome by standardising

FIG. 292



the complete set of apparatus, and this is done by inserting a non-inductive resistance in place of P, the primary coil under test, and measuring independently the power absorbed therein, as well as taking a reading on the wattmeter for this power. As the resistance is non-inductive there will be no lag; an electrostatic voltmeter can be used to indicate the virtual volts at its extremities, and a Siemens dynamometer to indicate the virtual amperes passing through it, and the product of these two will give the true value of the power absorbed. The wattmeter, with its auxiliary transformer, can then be employed to measure this known power, and the reading thus obtained will serve as a basis for standardising the instrument.

CHAPTER XIV

SECONDARY BATTERIES

IT was stated when describing the simple cell, that its great drawback, so far as concerned its general utility, was its comparatively rapid polarisation, a phenomenon which consisted in, or rather resulted from, the development of a film of hydrogen gas upon the surface of the negative plate. This hydrogen being an electro-positive element, a counter electro-motive force was set up, and the conditions for the flow of a counter-current thereby determined. But chemical reactions, similar to those which take place inside a battery cell, may be repeated in any part of the circuit by causing the current to pass through suitably arranged metals and liquids. The usual method of performing electro-chemical experiments is to attach metallic or carbon plates to the ends of the wires connected to the poles of the battery, and then dip these plates in a vessel containing the liquid upon which the current is to act. Thus, if the ends of two copper wires terminating in copper plates are connected to the copper and zinc poles respectively of the battery, and placed in a vessel containing acidulated water, then the passage of a current will cause a portion of that water to be decomposed, and the constituent gases, oxygen and hydrogen, to be released from their state of combination. The hydrogen will accumulate on the surface of the plate connected with the zinc pole, while the oxygen will combine with the other plate, just as it happened with the zinc plate in the simple cell. If, however, we substitute a strip of platinum for the copper plate connected with the copper pole of the battery, the liberated oxygen will not enter into any combination, but will remain in a gaseous state, a large portion of it rising into the air, and the remainder adhering to the surface of the platinum or entering its pores and becoming in

a measure occluded or absorbed by it. The absence of chemical combination between the platinum and oxygen is due to the weak chemical affinity subsisting between those two simple substances. By observing proper precautions the two gases may be collected separately, the apparatus for the purpose of producing the decomposition and collecting the products being called a voltameter. A serviceable form of this class of instrument consists of three vertical glass tubes, all in communication at their lower extremities, the middle one being taller than the others and terminating at the top in a small reservoir, to keep the two outer tubes supplied with solution, and to prevent the liquid overflowing when driven from them. Platinum wires are fused through the lower ends of the outer tubes and terminate inside in strips of platinum foil, which form the electrodes, their outer extremities being connected to terminals fixed on a wooden base. Taps are ground into the upper portions of the outer tubes, affording facilities for the escape, when required, of the confined gases. On sending a current through the solution the decomposition of the water takes place, the oxygen collecting in one of the outer tubes and the hydrogen in the other, according to the direction of the current. The water displaced by the gases collecting in the tubes shows readily that the quantity of hydrogen evolved is always twice that of the oxygen, in consequence of the fact that the gases unite in that proportion when combined to form water. If the platinum electrodes are now disconnected from the battery and joined up to a galvanometer, it will be seen that a current of electricity is produced by the voltameter, but that the direction of this so-called counter or secondary current is opposite to that of the battery or primary current which caused the separation of the gases.

A series of voltameters is, to all intents and purposes, a Grove's gas battery, each cell of which consists of two tubes, closed at the top and dipping into a glass vessel. A platinum wire is fused into the upper portion of each tube, and carries a long strip of platinum foil. Assuming the current from the battery to pass through the series, oxygen will be collected on one set of electrodes, while hydrogen will be collected on the other set. If, after the current has been allowed to flow for some little time, the terminals are connected to a galvanometer, a current will be observed to flow,

opposite in direction to the charging or primary current, and this reverse or secondary current, which is, after all, only the effect hitherto referred to as polarisation taking place under favourable circumstances, will continue to flow so long as the gases remain in contact with the platinum. As a matter of fact, we have set up a secondary battery with 'plates' of hydrogen and oxygen, and in maintaining the current, the hydrogen in one set of tubes combines with the oxygen of the water, forming new water molecules, while the equivalent hydrogen eventually released from the water combines with the oxygen in the other set of tubes. This action results, therefore, in the formation of water, as shown by the very simple equation :—

$$H_2 + OH_2 + O = OH_2 + OH_2 = 2\,OH_2.$$

We see here, then, an exact counterpart of the action that takes place in a primary cell, resulting there in the polarisation of the cell and the tendency to generate so-called secondary currents. The difference of potential or electro-motive force between the free hydrogen and oxygen is 1·47 volt, and this is a measure of the force of chemical combination between these gases ; whence it follows that, in order to overcome the force of combination, and therefore to decompose the water, we must employ for each such secondary cell an electro-motive force exceeding 1·47 volt.

Cells in which the energy of chemical change can be thus stored up, to be given out again when required, in the form of an electric current, are frequently called electrical accumulators or electrical storage cells. It is not, however, electricity which is stored or accumulated, but rather a quantity of the active constituents of a cell, and it is the subsequent chemical action between these constituents which causes the flow of electricity. It is therefore preferable to style them secondary cells. This will be more apparent when it is remembered that an exhausted primary cell can have a current sent through it in the opposite direction to that in which the current generated by it would flow, and this current will cause the usual negative plate to be more or less dissolved and the positive plate replenished, setting up the conditions necessary to the re-establishment of a primary current. If, for example, we suppose a powerful reverse current to be urged through a Daniell

cell in which the copper sulphate has been exhausted, the copper plate will be partially dissolved and copper sulphate re-formed, while zinc will be deposited upon what remains of the zinc plate. The cell is then able to again generate a current of its own.

Although the gas battery is exceedingly interesting, as a secondary generator it is not a practical piece of apparatus, for, on account of the limited quantity of gas which can be accumulated and rendered available, it is only able to maintain a current for a very short space of time. Many experiments have therefore been performed to determine the best liquid and electrodes (the metal plates immersed in the liquid) for a practical form of secondary battery. The most assiduous and successful worker in this field was Planté, and the result of his labours was the discovery that lead electrodes in a solution of sulphuric acid give the best results. Although he made his discoveries as far back as 1860, no more satisfactory combination has since been devised. He found that a large portion of the oxygen combined with the plate at which it was released, forming an insoluble compound, which when opposed to a clean metallic lead plate developed a potential difference of from 2 to 2·5 volts. In Planté's method the lead plates employed were comparatively large in area, with a view to increasing the amount of active material and reducing as far as possible the resistance of the cell. They were first laid one over the other, but separated by strips of non-conducting material, and then rolled up together in a kind of double spiral. In this way an extensive surface was presented to the liquid. On sending a primary battery current through the cell, from plate to plate, the water was decomposed, the oxygen combining with the metal at the positive electrode to form peroxide of lead, PbO_2, while the hydrogen was precipitated upon the negative electrode in the gaseous form, without in any way attacking the metal. The cell so acted upon became a secondary cell in which the negative electrode acted as the positive plate, being a sheet of lead with a partial film of hydrogen gas, the other plate or positive electrode with its film of insoluble lead peroxide behaving as the negative plate. It will thus be seen that the pole of the secondary cell which is connected to the positive pole of the primary generator, whether a battery or a dynamo machine, becomes the positive pole

of the cell when it produces its secondary current, the other extremity becoming perforce the negative pole.

On permitting the reverse or secondary current to flow, what remained of the hydrogen was oxidised and converted into water, some of the subjacent lead being also oxidised at the expense of the water. On the other hand, the peroxide on the other plate was deoxidised or reduced to metallic lead, in a 'spongy' form. These experiments can be very easily performed by sending for a short time a current from three or four good-sized Daniell cells through a vessel containing two pieces of sheet lead immersed in sulphuric acid solution. The piece connected to the copper pole of the battery will, after the passage of the current, assume a brownish tint, owing to the partial oxidation of the surface of the metal, while the piece connected to the zinc pole will assume the greyish colour characteristic of clean metallic lead. It should be noted that when the lead is first placed in the cell its surface is dulled by an oxide film, and the oxygen contained therein speedily enters into combination with the liberated hydrogen to form water, thereby leaving a clean metallic surface. The amount of chemical change taking place during these reactions is, owing to the limited extent of the surfaces, very small, and consequently when these lead strips are connected direct to a low resistance galvanometer, they will yield a current of but brief duration. The amount can, however, be increased by augmenting the lead surfaces (as Planté did), and by prolonging the time during which the primary battery is joined to the lead strips.

Returning to Planté's work, it was found by him that after sending the initial primary current through the secondary cell for some time, and thereby nearly covering the surface of the positive electrode with a film of the peroxide, the oxygen released from the water, instead of continuing to combine with the lead, formed into bubbles and escaped into the air. There was thus for a given metallic surface a limit to the amount of peroxide that could be formed. In order to increase this amount, the cell was allowed to discharge itself by generating a secondary current, which, as we have already learned, flowed in the reverse direction to the charging current. The consequence was that the lead

plate, acting as the positive of an ordinary cell, combined with oxygen, while the other plate which had previously absorbed a quantity of oxygen became deoxidised, and was, as we have already indicated, reduced to the condition of spongy lead, with a proportionally increased surface. A fresh direct or 'charging' current on being sent through the cell again oxidised this extended lead surface, and in its turn reduced the negative surface to the spongy lead state. These reversing operations being continued for some time, both positive and negative surfaces were eventually very considerably increased by the plates being rendered more or less porous, one of them, however, being always in a state of oxidation. After a few days a period of rest was allowed to intervene between the reversals, and during these periods the 'formation' of the plates was developed in a remarkable way by 'local action.' Dealing first with the period of rest after the passage of a charging current, the lead peroxide on the charged positive plate did not form a continuous impervious coating over the plate, but allowed the solution to pass between its particles and come into contact with the metallic lead. The peroxide being at places also in direct contact with the lead, a simple voltaic pair was thus established, with the lead for the positive and the peroxide for the negative elements. The acid attacked the lead and formed lead sulphate ($PbSO_4$), which is but a poor conductor of electricity; some of the peroxide was at the same time reduced to a lower form of oxide, probably the monoxide PbO. The amount of lead actually affected was thus increased, and the porosity of the plate gradually made more and more complete. In a somewhat similar way the surface of the negative plate was attacked during the interval of rest following a discharge, and the lead oxide distributed over the surface of the plate was in turn converted to lead sulphate. Lead being positive to its oxides, the pure metal would be attacked, during the local action that would ensue, and the sulphating is therefore easily accounted for. The development of the lead sulphate on the plates would not, however, increase the 'charge' given to the cell; in fact, if the cell were left idle for a considerable time, it would be eventually discharged by the gradual conversion of both the plates into lead sulphate. During the 'forming' process,

however, the development of the sulphate would be advantageous, as it has the effect of increasing the amount of lead surface available for subsequent charging and discharging. It will be seen that the process of forming the plates might have been continued until the whole of the lead became porous by its conversion into spongy lead; but there is a practical limit to the action, for if pursued too far, the plate would fall to pieces, simply on account of its inability to mechanically support itself.

The plates having been once formed, no further reversal is effected excepting for the purpose of discharging the cell to perform useful work.

This method of forming the plate is, however, very tedious and very expensive, and many efforts have been made to overcome the objection. One method is to subject the lead to a nitro-sulphuric acid solution which rapidly eats into the metal, and, rendering it more or less spongy or porous, increases its surface correspondingly. In another method the lead is in the form of corrugated thin lead strips about three-eighths of an inch wide, piled upon one another, so that when a leaden frame is cast round them they form a plate three-eighths of an inch thick, and of any desired length and breadth.

FIG. 293

Another form of lead plate consists of a single corrugated or grooved lead casting, the cross-section of a portion of one of these plates being illustrated on a considerably enlarged scale in fig. 293. The effect of these corrugations is to present to the solution a much larger surface than would be obtained with a smooth solid plate of the same external dimensions. The castings are by some makers 'boiled' in a weak nitric acid solution prior to 'forming,' in order to still further increase the surface, the subsequent treatment being exclusively electrical. The plates are immersed in a sulphuric acid solution, and the passage of the charging and discharging currents causes the usual spongy

formation as shown in the figure, but the lead peroxide and spongy lead thus formed adhere to the solid metal, and the consequent durability under rough or heavy usage is one of the chief advantages of this type of cell. It should further be noticed that the continuity of the solid metal involves a correspondingly low and uniform resistance.

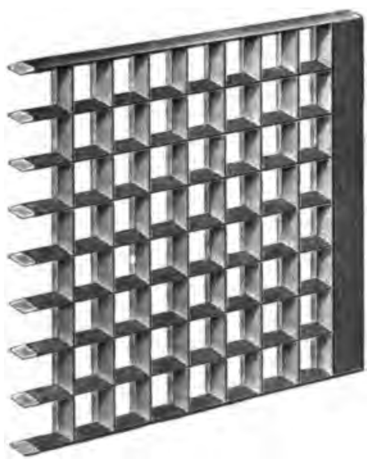
Lead plates pure and simple, when formed by the electrical process, are often known as Planté plates, but a type of cell more frequently employed is that which is based upon the principle which Faure enunciated in 1880, which was to coat the plates with a paste of lead oxide and acid, and so to more easily facilitate the extension of the lead surface. A mixture of sulphuric acid and minium or red lead (Pb_3O_4) was made, which resulted in the formation of a paste of lead sulphate ($PbSO_4$). This was applied to both the positive and negative plates, that on the plate in connection with the positive pole of the dynamo being, by the charging current, converted into peroxide of lead by the absorption of oxygen, while the paste on the other plate was reduced more or less completely to the condition of spongy lead. In this way the active surface speedily becomes considerable, and it will be seen that the great value of Faure's invention is to minimise the amount of energy required to be expended electrically as well as the time occupied in forming the plates.

It is now the general practice with 'pasted' plates to employ a paste of litharge (PbO) and acid for the plate connected to the negative pole, the employment of this oxide involving a smaller expenditure of energy in deoxidising than would be involved in the reduction of a higher oxide. In all cases, however, whether lead plates or pasted plates are employed, the ultimate result of the initial charging is the same, viz. the conversion of a portion of the positive plate into peroxide, and of the negative plate into spongy lead.

The Faure pastes adhere somewhat feebly to the lead plate, and many devices have been attempted to secure better adhesion. One of the earliest plans was to score or scratch the lead surface. Then it was indented, the indentations developing subsequently into perforations. The paste, on being squeezed into the holes, certainly kept its position much better than when

simply smeared over the roughened surface of the lead, but the quantity of paste exposed to the liquid was reduced. Eventually lead grids were cast of various designs but all containing sufficient metal to bear the weight of the complete plate. The Electrical Power Storage Company were the pioneer makers of cells with pasted plates. The grids have undergone a variety of changes, but we are able to give illustrations of a number of the designs which for the various purposes are now standard patterns. Fig. 294 is a full-size section of one of the positive plates of the so-called L type, in which it will be noticed that the holes are square and somewhat pyramidal—that is to say, smaller in the middle of the plate than on the surfaces, the object being to prevent, as far as possible, the peroxide from falling out. The negative grid is somewhat similar in design, the difference being that the plate is a little thinner and the holes a trifle larger than in the positive plate, as may be seen from fig. 295. In this form of plate, when properly treated, the pellets gradually get harder, until ultimately it is difficult to detach them. An illustration of the L type of cell is given in fig. 296. A number of pasted grids are used, the number varying with the size of the cell, but always with one negative plate in excess of the number of positive plates. The negative and positive plates are placed alternately, so that by employing a negative plate in excess of the number of positives, the two outer plates are negative, and there is a negative facing each side of every positive. The negative plates are all connected together, and so also are the positive, the object of having a large number of plates being, of course, to increase the capacity of the cell, and to reduce its internal resistance, without resorting to the

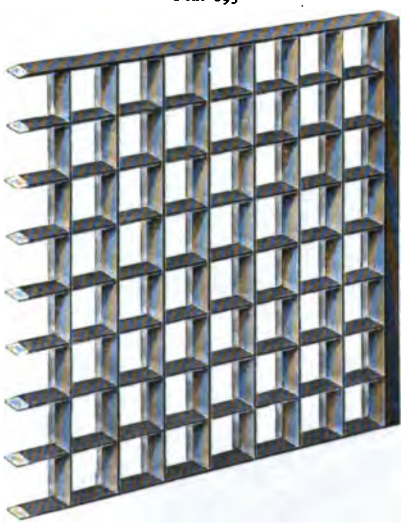
FIG. 294



use of inconveniently large plates. Each positive grid measures about $8\frac{1}{2} \times 9\frac{1}{2}$ inches, and is $\frac{3}{16}$ inch thick, the weight being about 5 lb.

The lead grids are provided with massive lugs for the purpose of connection, the lugs of the positive plates being all melted or cast on to one leaden strip or band, the lugs of the negative plates being similarly secured to another strip. The distance between two adjacent plates is about a quarter of an inch, which is usually sufficient to allow pieces of the plates or paste that may become

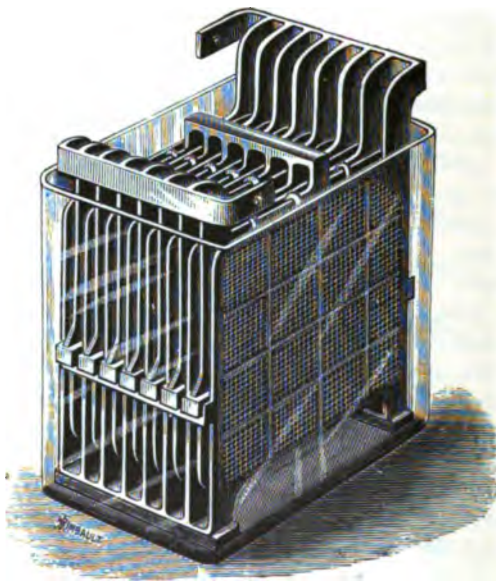
FIG. 295



detached to fall to the bottom of the cell. Bent strips or forks of ebonite, celluloid, or other suitable material, are placed between the plates to keep them apart and prevent internal contact. The negative plates in each cell are also held rigidly together by means of two stout strips of lead melted on to solid extensions from the lower edges, two others being also secured to the sides of the plates about half-way up. These connecting strips, one of which is shown at the left-hand side of the figure, serve as a further means of keeping the negative plates in position. The bottom strips rest on slabs or strips of paraffined or varnished wood, so as

to support them at a height of about 1½ inch above the bottom of the containing cell, affording thereby plenty of room for any scale or pellets that may fall to the bottom to lie clear of the plates. Lugs cast on to the edges of the positive plates rest in small ebonite shoes, which are supported by the side-strips of lead attached to the negative plates. The positives are also connected together across the top by the substantial lead strip shown a little to the

FIG. 296



right of the middle of the upper edges of the plates. The connecting strip to be seen on the left is melted on to projections from the corners of the plates, consequently they can be readily lifted out of the cell, without necessitating the removal of the negative plates. The largest cell of this type, which is primarily intended for electric lighting work, contains thirty-three plates (sixteen positive and seventeen negative) and has a maximum discharge rate of sixty-four amperes and a total capacity of

704 ampere-hours. The discharge rate for L type cells is four amperes per positive plate.

The containing vessels are best made of stout glass, an opportunity being thus afforded for the proper inspection of the cell, without taking it to pieces or removing the plates. The upper portion of the outer surface of the glass vessel should be coated with wax, vaseline, or some such material, to prevent 'creeping' and the partial short-circuiting of the cells by means of the continuous film of moisture that would otherwise condense over the whole of the external surface. When the cells are contained in glass boxes, the boxes should be bedded in sawdust contained in a varnished wooden tray. Each tray should stand on a number of special insulators (not less than four), according to the size of cell. The insulator is of the so-called Mushroom pattern, and a perspective view as well as a cross-section of one

FIG. 297

of these insulators is given in fig. 297. The channel in the lower cup contains, as shown in the sectional view of the insulator, a quantity of resin oil or of some other non-evaporating oil, in which the upper cup, coated with shellac varnish, rests.

The cells should not be quite in contact, but fairly close together, and the connections made either by 'burning' or melting the lead strips of adjacent cells together, or by clamping them firmly in a special form of lead or brass terminal. When the latter method is resorted to, and brass connecters are used, the connection should be painted over with vaseline, to protect the brass against the corrosive action of the acid, which, when the cell is well charged, sprays up considerably. This arises from the phenomenon known as boiling, and referred to on page 630. The gas-bubbles in their hurry to escape from the solution carry with them minute quantities of acid, but sufficiently numerous to

impregnate the atmosphere, and make it very unpleasant for any one entering a room where a battery is being charged and is at about its maximum voltage. In order to reduce this spraying as much as possible a loose sheet of glass is placed in each cell in an inclined position on the top of the plates, so that the spray striking against the glass is arrested, and the liquid accumulating in bubbles runs down the glass and back to the cell.

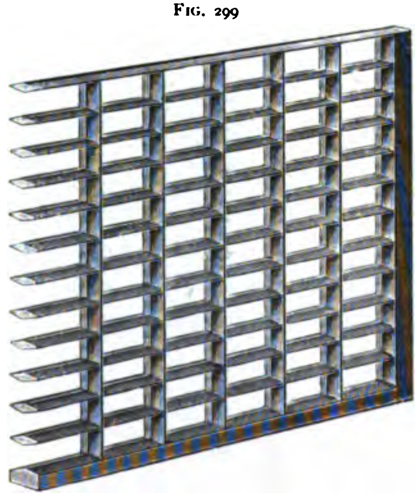
The positive pole of one cell is, of course, connected to the negative of the next, and so on. The positive connecting strips are usually painted red for the purpose of distinction. All wires should be as short and of as low resistance as possible, so as to avoid unnecessary waste of energy in overcoming the resistance of the connections. The resistance of secondary cells is very low, the current obtained from them is usually heavy, and, as we have indicated on a previous page, it often happens that the connections offer more resistance than do the cells themselves.

FIG. 298

It very frequently happens that it is required that a cell or a battery shall be capable of receiving a comparatively small charge maintained for a long time, and of discharging at a comparatively heavy rate for a correspondingly shorter period. For example, it would often be found convenient if a battery of L cells with 23 plates in each could receive its maximum charging current of 46 amperes for a period of 10 or 11 hours, and then give out, in discharging a current of, say, 90 amperes. This could no doubt be done as a matter of emergency, but if it were made the general practice the result would in all likelihood be disastrous, because when the discharge rate is excessive the active material expands, and there would in the case of grids such as are used in L type cells be a tendency to split the pellets and dislodge the peroxide. In view of the necessity for making provision for heavy discharge rates another form of grid has been designed. A full-size section

of one of these grids is given in fig. 298. It will be observed that there is a solid lead backing of considerable substance, and series of substantial lead ridges or shelves are provided to carry the peroxide. As the risk of splitting or disintegration is obviously very much reduced, the cells may be worked with safety at a correspondingly higher rate, plate for plate. The cell containing grids of this form for the positive plates is known as the W S type. The grid is of about the same area, but is nearly twice the thickness of the positive grid used in the L cell, and the negative grid, illustrated in fig. 299, is correspondingly thicker and heavier than the L negative grid. Glass tubes are used for separators, and are held in position both at the top and bottom of the cell. Glass tubes are extensively used, and they have two advantages, for they cannot bend and they are transparent. Of course the W S cell can be discharged at any rate below its maximum, and it will not be surprising to learn that as we increase the rate of discharge we simultaneously reduce the total output or efficiency. Cells of the W S type may with safety be discharged at rates varying from 8 amperes per positive plate when discharged in seven hours, to 15 amperes per plate when the discharge is completed in two hours. The cell with 23 plates may be charged with a maximum current of 124 amperes, but the most economical and effective rate is only one half of this maximum, and it may be interesting to note that a fully charged cell can on discharge yield a current of 88 amperes for seven hours, or a total output of 616 ampere-hours. If discharged at 132 amperes, the cell is exhausted in

FIG. 299



three and a half hours, or a total of 462 ampere-hours, while if discharged completely in two hours, the rate is 165 amperes, or a total output of only 330 ampere-hours. The drop in efficiency is very instructive.

The maximum working rate of the largest cell of the W S type is 180 amperes, but for central station and other similar heavy work a higher rate is required. To meet such demands, another type of cell, known as the P or power-station type, is manufactured. The positive plate is similar in section to that illustrated in fig. 298, but is much stouter and supports a considerably greater amount of paste, and the negative grid bears some resemblance to the grid

FIG. 300

illustrated in fig. 299. The cell is enclosed in a wood box lined with lead, the lead being brought over the top of the box and turned down about half an inch all round on the outside to prevent the creeping of the solution and the consequent leakage of the current. The cell has been designed to give a discharge ranging from a continuous discharge at the rate of 15 amperes per positive plate for seven hours to 50 amperes for one hour. It will here again be seen that the capacity of the cell at the slower rate is about twice as great as at the maximum rate. The largest cell made by the company is that known as the O K type, which is made up in boxes or crates of lead alloy and is supported by slate

trays. The positive plates are either of the Planté or of the pasted pattern; the former is illustrated in fig. 300, and the grid of the latter in fig. 301. The increase in the surface of the metal to be oxidised in the case of the Planté plate is enormous, and in course of time a very large percentage of the material of the ridges will be converted into peroxide. The pasted plate is similar in design to that used in the W S cell, but it is very much heavier, and it will be noticed that additional strength is given to it by means of a number of vertical webs at intervals of an inch. The negative grid is illustrated in fig. 302. In this case the grid is very open. In design it consists of a pair of light gratings with a number of horizontal shelves between them and extending the whole length of the plate. A very large quantity of paste can obviously be stored in such a grid, and in no case is the difference in the requirements for the positive and negative plates so well pourtrayed as in this case. Were such a grid as that depicted in fig. 302 used for a positive plate it would undoubtedly fall to pieces in a very short time. The grid is about half the thickness of the positive grid illustrated in

FIG. 301

FIG. 302

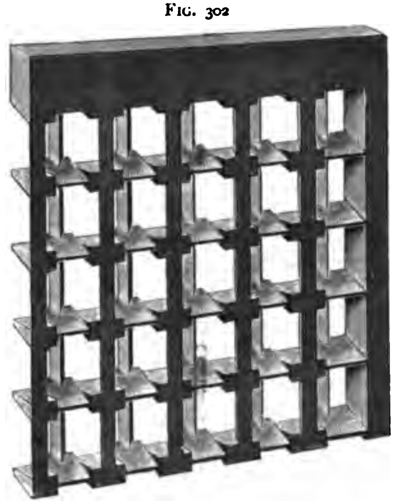


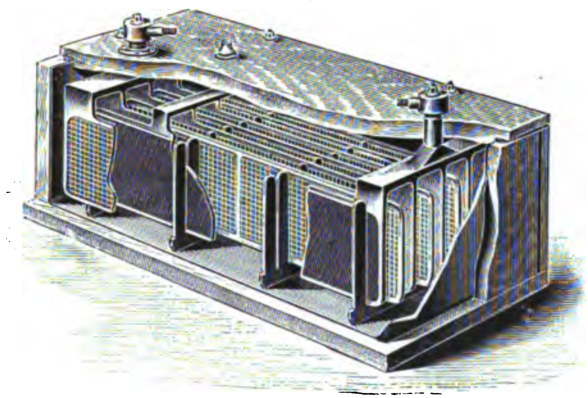
fig. 301. These cells are designed for large power stations, more particularly where floor space is restricted. The largest cell of the type has 41 plates, 20 positive and 21 negative. It measures 1 ft. 11½ in. long by 3 ft. 8 in. wide. The height of the box is 2 ft. 5½ in., and the height of the cell over all, including tray and insulators, is 2 ft. 10½ in. When filled with solution it weighs 2850 lb. The maximum charging current is 1000 amperes, the most economical being, as in the case of the other rapid discharge cells, one half of the maximum. The discharge rates are 700 amperes for seven hours, 1100 amperes for three and a half hours, and 2000 amperes for one hour. These figures represent 35, 55 and 100 amperes per positive plate, and total outputs of 4900, 3850 and 2000 ampere-hours respectively. Thus it is again shown that the capacity of the cell at the slowest of these rates is more than twice as great as at the maximum rate, and once more the figures emphasise the fact that the slower the rate of discharge, the greater is the amount of energy which is given back by a cell. Similarly the most economical rate of charging is one-half of the maximum rate, because, among other things, at the maximum rate oxygen is released faster than it can be absorbed, and the cell boils prematurely.

There are many other types of cell designed for a variety of purposes, amongst which we may mention the propulsion of road vehicles, cases in which the cells have to be made up in a portable form. Fig. 303 illustrates a form of cell of this kind constructed for train lighting. It is enclosed in a teak box lined with lead, and contains, to suit different requirements, either nine or fifteen plates separated by celluloid forks. Sometimes, in order to further reduce the risk of contact and short-circuiting between adjacent plates, thin perforated celluloid sheets are interposed between them. Connection between adjacent cells is, of course, made externally, rods attached to the connecting strips passing through the covers for the purpose. Connecting rings fit on to these rods, through slots in which wedges are driven to secure good electrical contact, the rings of adjacent cells being joined together by stout wires or rods. The peculiar shape of the forks shown in fig. 303 should be noticed.

When the work which a particular battery is called upon to

perform increases so far as to exceed its capacity, it becomes a question whether the battery should be replaced by one of larger capacity, or whether a second similar battery should be provided and joined in parallel. The course to be adopted depends very largely upon the circumstances, but if the plates are old or in bad condition it will generally be found more satisfactory to replace the cells by others of larger capacity. When the circumstances are such that parallelling is decided upon as being the more desirable, it should be remembered that there are two ways of effecting this. One is to join the terminals of the two complete batteries together,

FIG. 303



and although this is the more satisfactory method, some difficulty is usually experienced in keeping the two sets at a common potential difference. In order to ensure that the two shall be equally worked, a separate ammeter should be inserted between one terminal of each set and the point where the two sets are joined together. The other method is far less satisfactory, and consists in joining the cells in parallel in pairs, and then joining the various pairs in series. It should be evident that it is almost impossible to maintain each pair of cells at a common potential (indeed it is not always easy to ensure this in the case of the various plates in any one cell), and when this is not done a wasteful expenditure of energy must ensue.

A few details concerning some of the various types of E. P. S. cells will doubtless prove of service. In the subjoined table, L indicates cells for lighting and general purposes, W S a high discharge type for general purposes where an occasional heavy current is required for short periods, P a large cell for power purposes, O K the largest type for central station work, W T a special type for ship lighting, C for train lighting, T for tram-cars &c., and Q a class of cell serviceable for small work, such as testing.

Description of Cell		Working Rate		Capacity	Approximate External Dimensions			Acid 1·200 sp. gr. for each cell	Weight of Cell complete with acid
No. of Plates	Material of box	Charge Amperes	Discharge Amperes	Ampere-Hours	Length	Width	Height over all		
					in.	in.	in.	lb.	lb.
L 15	Teak	25 to 30	1 to 30	330	9⅝	13¼	20¼	40	152
	Glass	25 to 30	1 to 30	330	9¾	13	18	52	142
L 33	Teak	54 to 64	1 to 64	704	20¼	13½	20¼	84	322
	Glass	54 to 64	1 to 64	704	20¼	13	18	115	310
W S 15	Glass	40 to 80	56 to 105	210 to 392	14	13	20	80	244
W S 25	Glass	67 to 135	96 to 180	360 to 672	20¼	13	20	115	375
W S 115	Teak	303 to 605	440 to 825	1650 to 3080	60	20¼	19½	430	1650
P 25	Teak	150 to 300	180 to 600	600 to 1260	18¼	24¼	26	216	890
P 57	Teak	350 to 700	420 to 1400	1400 to 2940	18¾	53	26	500	1930
O K 25	Lead	300 to 600	420 to 1200	1200 to 2940	23¾	27	34¼	383	1805
O K 41	Lead	500 to 1000	700 to 2000	2000 to 4900	23½	44	34½	630	2850
W T 15	Teak	40 to 80	56 to 105	210 to 392	13¾	14	22	60	236
W T 33	Teak	90 to 180	128 to 240	480 to 896	27¼	15¼	22	135	525
T 15	Teak	24 to 28	1 to 30	95	9¼	8⅞	13¾	14	52
	Ebonite	24 to 28	1 to 30	95	8	7¾	12¼	14	42
C 15	Teak	12 to 14	1 to 14	136	9½	13¼	9	14	62
Q 3	Teak	·5 to 1·3	1·3	7	2	5⅝	9¼	·9	6
Q 21	Teak	10 to 13	13	70	9	5⅝	9¾	6·5	28

One other type of cell, that known as the Chloride cell, calls for a brief description. The process of manufacturing the negative plates is somewhat elaborate. Litharge is first dissolved in acetic acid, and thereby converted into acetate of lead. This is placed in a solution of hydrochloric acid, where the acetate is converted into chloride of lead, which, being insoluble, is precipitated. The precipitate is filtered, and after being pressed into slabs is dried in an oven; it is next intimately mixed with finely divided zinc, and the mixture is then melted in large pots. The mixture is then cast into small hexagonal slabs or 'pastilles.' These pastilles are arranged symmetrically in the plate-moulds. These moulds

contain a number of small pegs, and each pastille has two small holes cast into it, so that the pegs fitting into the holes keep the pastilles properly distanced. A substantial lead grid is then cast round the pastilles under considerable pressure, the metal being thereby forced into very intimate contact with the pastilles. The plates thus constructed are placed in a solution of chloride of zinc, and are alternated with plates of metallic zinc. The necessary connections being made, the zinc plates act as the positive plates in a primary cell; the zinc, which would otherwise be deposited on the negative plates, or the lead plates carrying the pastilles, enters into combination with the chlorine of the chloride of lead, leaving the lead in a spongy condition. The zinc which was mixed with the chloride of lead is also converted into chloride of zinc and enters into the solution. The pastilles are consequently reduced to the condition of metallic lead in a very porous or spongy condition. When this part of the process has been completed the plates are thoroughly washed in running water and are afterwards placed in a weak solution of sulphuric acid, where they again act as negative plates, the other plates being ordinary positive plates. A current is sent through the cell, and hydrogen being in the ordinary way liberated at the surface of the negative plates, effectually removes any trace of chlorine which might have been left by the previous processes. In this way the negative plates are completed and have given them an extensive area of metallic lead in contact with the solution. The positive plate is prepared by first winding a quantity of 'gimped' lead ribbon into circular coils or slabs, and driving these coils into round holes provided in a substantial lead grid. These positive plates are then 'formed' by sending a current through a cell containing a number of the plates joined to the positive pole of the dynamo. A layer of lead peroxide is therefore produced on the extensive surfaces of the little coils of lead. The two sets of plates having been prepared are melted on to substantial lead bars in the ordinary way and are then ready for work. Cells of this type are extensively employed for central station work, and appear to be giving good results as regards both capacity aud durability.

Secondary cells are usually delivered by the makers in a dry state and uncharged, and in making them up prior to charging,

the solution should be poured in to the height of about ½ an inch above the negative plates. The solution should consist of pure soft water and pure sulphuric acid of 1·84 specific gravity, and sufficient acid should be added to the water to raise its specific gravity to 1·200 (that is, if a given volume of water weighs, say, 1 lb., the weight of an equal volume of the solution should be 1·200 lb.). The specific gravity of the solution in the 'unformed' cell will fall prior to the charge, and the charging current will have to be maintained for some time before the specific gravity rises. It will, however, be seen from the equations given in this Chapter that, in the process of charging, some of the water in the cell is changed to sulphuric acid, and this causes the specific gravity to rise ultimately to about 1·220. This accretion of sulphuric acid, which is, however, lost on discharging the cell, is accompanied by an increase in the conductivity of the liquid to the extent of about 10 per cent. During the discharge the density of the solution falls until, when the cell is practically exhausted, it is only 1·150. The relative density of the solution thus affords an excellent means of ascertaining the condition of the cell, and an instrument for measuring the specific gravity of the acid solution becomes, therefore, a necessity. Such a piece of apparatus is called a hydrometer, or, for this special case, an acidometer, a useful form being that shown to the left in fig. 304, which is simply a glass tube weighted at the bottom with a quantity of small shot. The lower the specific gravity of the solution—that is to say, the lighter it becomes bulk for bulk—the deeper will the hydrometer be immersed. As the liquid

FIG. 304

increases in density the instrument becomes relatively lighter and therefore rises. Consequently, the scale on the tube can be made to indicate the relative density corresponding with the various depths to which the tube descends. The other form illustrated in fig. 304 is that known as Hicks's hydrometer, which is, however, comparatively expensive. It consists of a flattened glass tube with the upper end bent over so as to allow it to hang on the edge of the glass containing vessel, the tube being also perforated to facilitate the free circulation of the solution. Inside the tube are four small glass globules containing liquids of different specific gravities and different colours; each globule rises and falls at distinct specific gravities and allows thereby the relative density of the solution to be very readily ascertained.

It may be observed that the colour of the plates affords another good indication of their condition, the peroxidised positive plate being, when in proper condition, of a brownish or deep reddish hue, the negative or spongy lead plate being coloured grey or slate tint. There is thus a marked distinction in the coloration, which should always be discernible.

There are various explanations of the chemical changes which take place in a secondary cell, but although many of the most brilliant chemists of the day have devoted considerable attention to the subject it is still shrouded in doubt, and there seems but little probability of a general concurrence of opinion as to what actually takes place. The difficulty arises from a number of intermediate or secondary reactions, which, it is assumed, take place during the processes of charging and discharging.

We are, however, more particularly concerned with the final rather than with the intermediate stages, and will therefore assume that our plates, whether they be of the Planté or of the Faure or pasted type, have been duly formed and charged, so that the positive plates have been coated with lead peroxide (PbO_2), and the negative plates reduced to the state of spongy lead. The condition of the cell can then be represented by the symbols :—

$$\underset{\text{Lead peroxide}}{PbO_2} + \underset{\text{Sulphuric acid}}{SO_4H_2} \;.\;.\;.\; \underset{\text{Sulphuric acid}}{SO_4H_2} + \underset{\text{Lead}}{Pb.}$$

This means that the active material on both plates is in contact with the sulphuric acid solution. If now the cell is discharged the two plates are partially converted into sulphate of lead, and the changes which take place can be represented by the following equation:—

$$\underset{\substack{\text{Lead}\\\text{peroxide}}}{PbO_2} + \underset{\substack{\text{Sulphuric}\\\text{acid}}}{SO_4H_2} \ldots \underset{\substack{\text{Sulphuric}\\\text{acid}}}{SO_4H_2} + \underset{\text{Lead}}{Pb} = \underset{\substack{\text{Lead}\\\text{sulphate}}}{PbSO_4} + \underset{\text{Water}}{OH_2} \ldots \underset{\text{Water}}{OH_2} + \underset{\substack{\text{Lead}\\\text{sulphate}}}{PbSO_4}$$

Combining the changes on the two plates into a simple chemical equation, we get

$$PbO_2 + 2\,SO_4H_2 + Pb = 2\,PbSO_4 + 2\,OH_2.$$

We thus see that for every atom of lead attacked during the discharge both on the positive and on the negative plates, a molecule of sulphuric acid is decomposed, and the solution is further diluted by the formation of a fresh molecule of water. When the active portions of the plates have been more or less completely converted into lead sulphate, no further current can be obtained. This should be evident when it is remembered that the first essential in a cell is to obtain two plates whose surfaces are dissimilar. The cell having been discharged, a further charging operation is therefore necessary before any further current can be obtained. The chemical effect of the charging current is exactly the reverse of that which results from the discharge, as will be gathered from the equation:—

$$PbSO_4 + OH_2 \ldots OH_2 + PbSO_4 = PbO_2 + SO_4H_2 \ldots SO_4H_2 + Pb;$$

or, again, combining the two changes, we get

$$2\,PbSO_4 + 2\,OH_2 = PbO_2 + 2\,SO_4H_2 + Pb.$$

The reversal is thus very complete; the two plates are reduced from lead sulphate to lead peroxide and spongy lead respectively, while the solution regains the sulphuric acid which was extracted from it during the discharge. The water which was formed during the discharge is also completely absorbed during the charge.

These reactions, however, affect only a portion of the plates; in fact, the active portion of the cell is usually very much less than that which remains passive.

Fig. 305, which is very instructive, is the outcome of a series of experiments by Messrs. Ayrton, Lamb, and Smith, as well as of

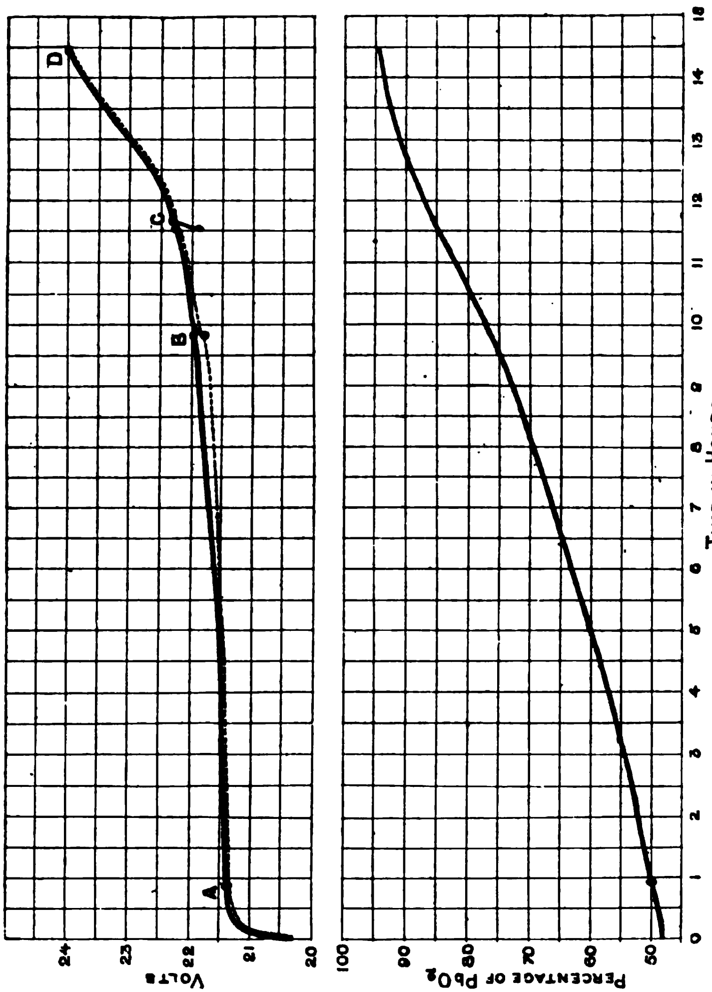


Fig. 305

a number of chemical analyses by Mr. Robertson. A cell which had been carefully worked, and was therefore in good condition,

was charged in the ordinary way for 14½ hours with a current of 9 amperes. The gradual rise in electro-motive force is indicated by the dotted curve. The cell was then discharged for about 12 hours at the rate of 10 amperes. During the next charge, however, which is indicated by the continuous curve, the positive plates were temporarily removed from the cell at the points marked A, B, C, and D, when the terminal potential difference of the cell was 2·134, 2·2, 2·234, and 2·4 volts respectively, and some of the pellets were forcibly removed and subjected to chemical analysis. The interval that elapsed during the removal of the pellets (about twenty minutes on each occasion) is not shown in the curve, the potential difference indicated a few seconds after again closing the circuit being the same as that which was observed at the moment of disconnecting the charging circuit. The pellets were taken from the top, middle, and bottom of the plates, and every care was exercised to avoid the introduction of any disturbing element or anything likely to prejudice the results of the analysis, which showed (fig. 305) that the percentage of lead peroxide contained in the pellets increased as the charge progressed. Similar experiments were made by removing pellets during the discharge, and it was found that the percentage of PbO_2 fell at approximately the same rate as that at which it rose during the charge. An interesting feature brought out in these analyses is that 48 per cent. of the PbO_2 found in the peroxide pellets does not suffer conversion into lead sulphate—that is to say, it exceeds by this amount the quantity actually essential to the reactions. The explanation is that the sulphate of lead which is developed forms an impervious coating over the surface of the pellets, and thus prevents the action from extending to the inner particles.

Mr. Robertson's analyses may be thus summarised:—

'(*a*) The particles of the peroxide very soon get coated in the discharge with a layer of lead sulphate, which protects the peroxide from further action.

'(*b*) The analysis also shows that a large proportion of active material is still remaining at the end of the discharge.

'(*c*) The loose powdery surface of the positive plate seems to be thoroughly converted into lead sulphate.

'(*d*) When the peroxide on the surface of the plate falls to about 31 per cent. the cell loses its E.M.F. very rapidly owing to the inactive layer of sulphate impeding the action of the sulphuric acid on the active material behind it, and also to the formation of peroxide on the negatives. The "diffusivity" of the acid is also then decreasing, while it has to penetrate further into the plate to find active material. When the whole of the paste approaches the composition of 31 per cent. peroxide, the cell loses its E.M.F. entirely.

'(*e*) The action seems to take place most rapidly where the current-density is greatest; the plate gets hard there from sulphate soonest on discharge, and oxidises quickest on charge.'

It has been observed by Planté, as well as by Messrs. Gladstone and Tribe, that during the discharge of a cell a certain amount of peroxide is formed upon the negative plate, so that when the peroxide is thus formed at a greater rate than it is reduced by the acid, the two plates, positive and negative, must approach a state of electrical equilibrium. Further, when the circuit is broken, local action alone can take place, the effect of which is to reduce the peroxide on the negative plate—that is to say, the peroxide will be deprived of its oxygen. Consequently, on remaking the circuit, the cell will again give a current. This idea had been used by Messrs. Gladstone and Tribe to account for the so-called recuperative power of a cell, as well as for the rise of electro-motive force which is observed on breaking the discharging circuit. It is a matter of general knowledge that if a cell be discharged so far that it will yield only a very feeble current—so far, that is to say, that its electro-motive force has fallen almost to zero—it will, after a period of rest, be found to have a considerably higher electro-motive force than at the moment when it was disconnected; and that this recuperation enables it to send a comparatively strong current through the circuit.

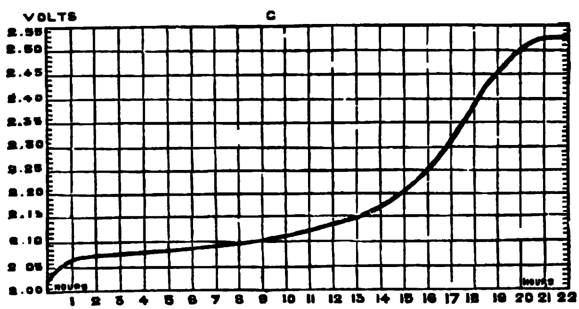
It will be evident that while it is essential that great care should be exercised in the manufacture of secondary cells, the treatment to which they are subjected is a matter of at least equal importance. The charging current should be proportional to the number and area of plates, and for the L type of cell, described on a previous page, should be equal to about 4 amperes per positive

plate, so that the 15-plate cell requires from 25 to 30 amperes. When the current exceeds this amount, it cannot increase the reduction of the sulphate of lead in proportion to the extra amount of current, and the surplus current is therefore wasted in the decomposition of water and the premature evolution of bubbles of oxygen gas from the positive surface, a phenomenon which is technically known as boiling. There is a certain amount of risk that the too powerful current will cause bending or buckling of the plates, which, being usually close together, are liable to make contact one with the other, and so short-circuit the cell. The electro-motive force of the charging current should exceed that of the subsequent discharging current by about 10 per cent., being, however, a little less at starting than when approaching the completion of the charge. This should be evident when it is remembered that the counter electro-motive force of the cell rises as the charging and consequent chemical reactions progress; for example, if the cell is so far charged that its electro-motive force is two volts, it would require a smaller applied potential difference to urge a current of 30 amperes through it than would be necessary when the electro-motive force of the cell has been raised to 2·5 volts. In practice the object when charging from a fixed E.M.F. is attained by switching cells out of the circuit, one or two at a time, as the electro-motive force of the battery rises. When, however, a separate dynamo is used for charging purposes, the variation in E.M.F. can be easily effected by inserting an adjustable resistance in the field-magnet circuit at the commencement of the charge, and gradually reducing this resistance as the E.M.F. of the cell rises. The reduction of the resistance involves, of course, an increase in the strength of the field, and therefore in the voltage developed by the armature. The charging should be continued until the solution 'boils' freely or assumes a milky appearance, consequent on the evolution of oxygen gas, the positive plates having then been oxidised as far as possible, or having absorbed as much oxygen as they can take up. This so-called boiling is one of the most useful indications of the condition of a battery as it approaches the end of its charge. As a general rule the charging current should be maintained until every cell assumes the milky appearance indicative of the free

evolution of gas-bubbles. If any particular cell should remain obdurate, the probability is that it is short-circuited, and it should be carefully examined, and, if necessary, removed from the battery, its place being taken by another cell while it is being overhauled and re-charged.

The E.M.F. of a secondary cell, as was shown in fig. 305, does not rise uniformly with the continuance of the charging current. In some experiments, performed with a battery of 15 cells, a current of 22 amperes was employed, by which the E.M.F. was raised from 2·02 to 2·53 volts per cell. The variations in the rate of increase are shown in fig. 306, from which it will be seen that after 220 ampere-hours had been put in—

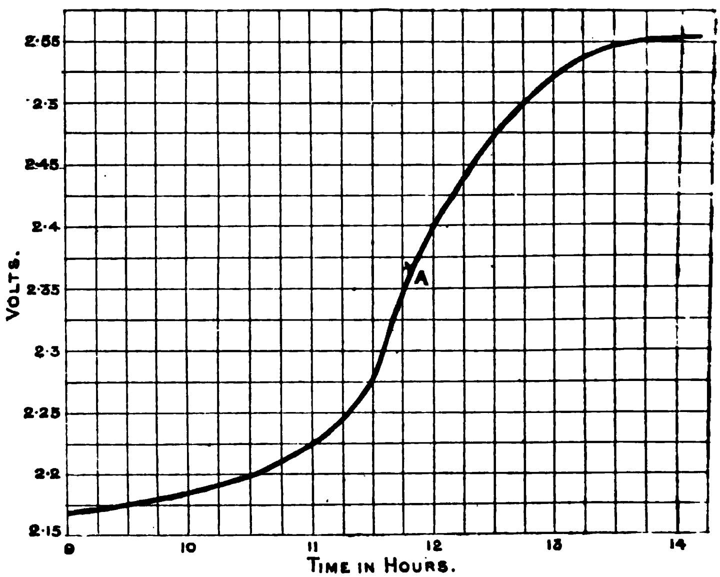
FIG. 306



that is to say, after a charging current of 22 amperes had been maintained for a period of 10 hours—the E.M.F. had risen gradually to 2·13 volts. After about 14 hours' charging, when the E.M.F. was 2·17 volts, a somewhat sudden rise in E.M.F. was observed, which was continued until 2·53 volts were registered. The maximum E.M.F. usually obtained is 2·5 volts, at which point gases are freely evolved, and cause the milky appearance already referred to as boiling. It has been conclusively proved that overcharging, although generally involving a waste of energy, is not only harmless, but may in certain circumstances be beneficial. In the experiments referred to some cells were charged without cessation, until the full prescribed current had been passed through, for more than two months. At the end of that time it was found

that the lead conductor was practically as sound as before charging. The coating of fine peroxide formed on the surface was very thin; there was no sign whatever of buckling, and further, the specific gravity of the solution, when the cells were left in their then fully charged condition, remained absolutely unaltered. The conclusion thence drawn was that the oxidisation of the grid caused by charging only penetrated to a very limited depth, and that the coating of fine peroxide thus formed actually

FIG. 307



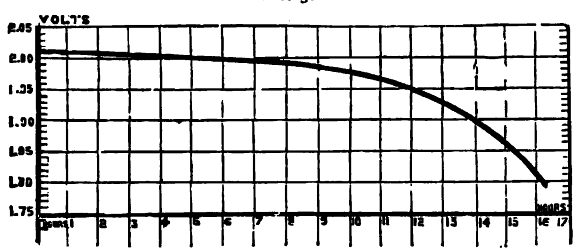
protected the grid from excessive local action; and it was established that the life of the grids was not limited by the amount of charging, *i.e.* by the number of ampere-hours put into a cell. We shall return to this question presently.

Professor Ayrton and several of his assistants have obtained a valuable series of curves, one of which is reproduced in fig. 307. In this case the cells were charged with a current of 9 amperes. The rise in potential difference was slow and steady up to about

2·15 volts per cell, but then became much faster, until a maximum of 2·55 volts was obtained. The most rapid increase occurred at about the end of the twelfth hour of the charge, as indicated at A in the figure. The similarity between this curve and that given in fig. 306 is very noticeable.

During the discharge the E.M.F. of the cells speedily falls to about two volts each, the higher initial electro-motive force being mainly due to the presence of hydrogen on the spongy lead plate. When this has been oxidised there remains the lead surface, between which and the peroxide plate the electro-motive force falls very slowly to about 1·98 volt. The fall is then slightly faster, although, as was found in the series of experiments referred to on page 631, after an output of 400 ampere-hours at the rate of

FIG. 308



25 amperes, the total drop from the time that the cell settles down to steady work at 2·02 volts is only about 10 per cent. The rate at which the fall of E.M.F. took place is clearly shown in the instructive curve given in fig. 308. The discharge was continued until the E.M.F. was 1·80 volt per cell. With a fall to 1·90 volt the difference is only about 5 per cent.

In an experiment performed to ascertain the effect of a rapid discharge upon the plates, a battery was divided into two halves, one of which (A) was repeatedly run out, and the other (B) was never discharged beyond the point at which the E.M.F. commenced to drop. The experiment extended over a considerable time, but gave the instructive result that when exactly the same number of ampere-hours had been taken out of each half, the plates of (A) showed signs of expansion or growing and consequent buckling,

whereas in those of (B) no change could be detected. The life of the grid was therefore proved to be dependent not so much on the number of ampere-hours taken out, or on the work done, as on the rate of discharge.

Fig. 309 is a portion of the discharge curve obtained by Professor Ayrton and his collaborateurs, but it differs from that given in

FIG. 309

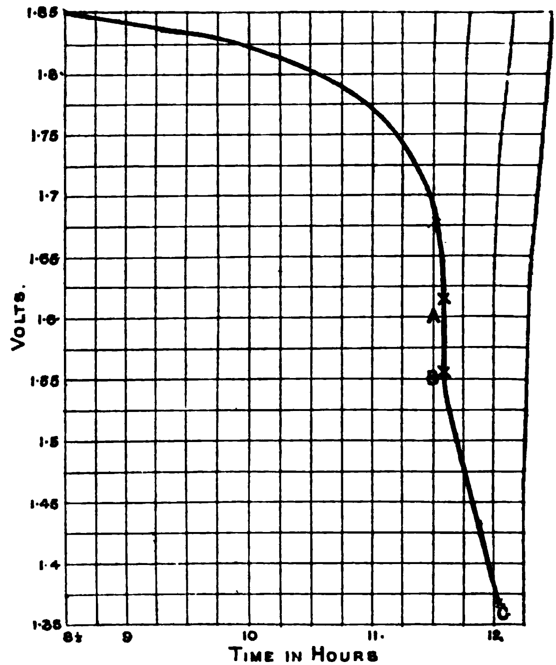
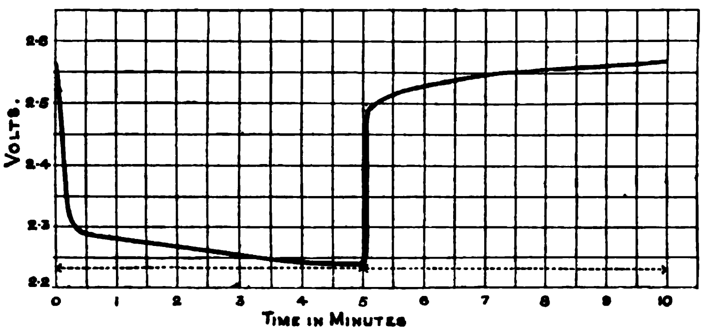


fig. 308, in that the discharge, which was at the rate of 10 amperes, was continued until the potential difference was reduced to 1·35 volt, and the rapidity with which this potential difference falls from about 1·75 volt is very remarkable. Another very instructive curve obtained from the same series of experiments is that given in fig. 310. The cell was charged with a constant current of 9 amperes until a potential difference of 2·56 volts was obtained. The charging

circuit was then broken, and immediately there was a fall to 2·31 volts, followed by a steady fall during the next five minutes to 2·24 volts. On again closing the charging circuit there was an instantaneous rise to 2·48 volts, followed by a steady rise during the next five minutes to 2·56 volts. In subsequent experiments it was ascertained that the fall of potential difference, on disconnecting the charging circuit, became more rapid as the charge increased.

It should be observed that by the time the E.M.F. of a cell discharged in the ordinary way has dropped to 1·90 volt the greater portion of the surfaces will have resumed the condition of lead sulphate ($PbSO_4$), and there will then be considerable risk of the formation of a more obdurate form of sulphate, which may be

FIG. 310



expressed by the symbol Pb_2SO_5, and which is caused probably by the $PbSO_4$ combining with the monoxide or PbO. This is a hard white sulphate and is very troublesome. It is insoluble, non-conducting, very adhesive, and covers both the pellets and the grid, and in very bad cases forms on the inside of the plate between the grid and its pellets. When it falls off the plate, it generally carries with it some of the active material, which is therefore wasted. It is consequently advisable that the E.M.F. of the individual cells should be tested periodically with a low-reading voltmeter, but this instrument should be of high resistance, say 200^{ω} or more, and of a type which is not liable to vary in the presence of adjacent masses of iron or other similar

disturbing influences. A modification of the movable coil type (Chapter IV.) is the most serviceable.

The phenomenon known as buckling, and to which reference has already been made, is almost invariably accompanied by the formation of the hard sulphate on the face of the plates, and it is generally conceded that buckling is a consequence of over-sulphating. When the plates are free from sulphate there is no tendency to buckle. It is interesting to note that in the case of the first use of cells the specific gravity of the solution drops somewhat as soon as it is introduced, and that it continues to fall for some little time after the charging current has been switched on. This is indicative of the absorption of acid by the plates, but, of course, the continuance of the charging current under normal conditions speedily reduces such sulphate as may have been formed, and with it the tendency to buckle. In order to avoid buckling of the peroxide plates, cells on their first use (whether new or after long disuse) should be charged incessantly until they have been considerably overcharged; neither should they in the course of working be discharged either too rapidly or below a voltage of 1·9 as a regular thing, or 1·85 on emergencies.

It has been ascertained that in almost every case where abnormal disintegration takes place, the plugs of active material fall out of the plates in complete halves and in very hard condition; and analysis has shown that they contain an excess of sulphate. On the other hand, in a few instances the active material has been found to have become disintegrated and fallen off in a fine powder, and this was specially observable when, on account of a leak in the containing-vessel and consequent frequent addition of water, the solution had become abnormally weak. In this case practically no sulphate was present, and the mass simply lost cohesiveness. Of course, this fault could not happen if proper use were made of hydrometers for the purpose of regularly and systematically ascertaining the specific gravity of the solution.

As has already been intimated, buckling is due to the expansion of the paste during sulphating, and arises from the fact that lead being a very ductile but non-elastic material, the grid does not re-assume its original shape when the subsequent partial contraction of the paste takes place, and to this is also attributed

the loosening of the pellets. The contraction being but partial, the positive plates become gradually increased in size with continued use. It is therefore necessary that the grid should be of uniform strength throughout, and not made stronger in one direction than in another. Efforts have been made to harden the grid by the admixture of a small percentage of antimony, but some difficulty is experienced in making the alloy of uniform proportions throughout.

The growth of the plates consequent upon buckling is somewhat considerable. Mr. Reckenzaun found that a positive plate, which had when new a surface of 90 square inches, grew to 94·76 inches after one year's daily use, while others showed, when almost worn out, an increase of 7 square inches ; these measurements being simply the product of the length into the breadth of the plate, and independent of corroded or oxidised furrows. The actual amount of surface in contact with the liquid is considerably greater than these figures would indicate, owing to the irregularities produced by the solution.

The evil effects of an excessive discharge either in rate or in extent may therefore be briefly summarised by saying that there is a considerable risk of causing unequal expansion of the plates, resulting sooner or later in buckling, loosening of the active material, and short-circuiting.

The life of a positive plate is not, however, so brief as might be anticipated from the many little difficulties which beset it, for with fair and continuous usage its life amounts to about three years, or at the normal rate of working it will sustain about 1000 discharges. The decay of the plate is more rapid in the lower than in the upper half, owing probably to the greater density of the acid solution in that portion of the cell. The life of a properly used negative plate, which is subject to but few of the troubles attending the positive plate, is estimated at ten years.

The capacity of a cell may be defined as the amount of energy it is capable of storing, and is calculated generally in ampere-hours : that is to say, it is the product of the number of amperes at which the cell is able to discharge, into the number of hours through which it can maintain that discharge. Capacity is also estimated by the ratio between the weight of the material and the electrical

output. The amount of surface exposed to the solution really determines the charge which a cell can receive, and is therefore a measure of its capacity. The capacity of a cell is an important consideration, seeing that the prime cost is considerable, that the cell is bulky and therefore requires correspondingly ample accommodation, and that only a portion of the plate is utilised. The capacity can be increased by more thoroughly 'forming' the paste and reducing the proportion of solid metal, which we may call so much dead weight, but it is not safe to carry this reduction much further than has already been done, or there will be considerable risk of the plate being unable to bear its own weight, and therefore of its falling to pieces.

Many attempts have been made to use other electrodes than lead for secondary cells, but with little success. Thus one was constructed in which there was a lead plate to be peroxidised, the other plate consisting of copper to be alternately dissolved and deposited from a copper sulphate solution; but the low electromotive force of this cell precluded its adoption. For somewhat similar reasons the employment of other suggested solutions has been found to be impracticable, and there is therefore no need to further discuss them here.

Coming now to the question of 'efficiency,' or the ratio of the energy taken out of the cells as compared with that put into them, the former can, of course, never equal the latter. The phenomenon of boiling, for example, is an evidence of energy being wasted, for the current is then employed in the unproductive decomposition of water. It is often asserted that secondary cells are capable of giving out 75 or more per cent. of the energy put into them, and this may be true with small cells wholly but slowly discharged; but the experience of those who have given the matter long and earnest attention is that the efficiency of cells of the ordinary sizes, discharged at the normal rate, to their proper minimum E.M.F., ranges after a few months' use from 50 to 60, or at the very outside, 65 per cent. Even then great care has to be taken that the charging current is of the right strength and potential difference, and that the cells are maintained in the best possible condition. Our own experience is that under ordinary working conditions, and allowing for all losses, the efficiency of a secondary

battery averages 55 per cent. or thereabouts. The efficiency of a cell depends, as will probably have been gathered from what has already been said, very largely on the rate at which the energy is discharged : that is to say, it depends upon the current strength per unit of surface or, as it is technically termed, upon the 'current density,' and it may be stated generally that the lower the density, the greater the efficiency. With a 25-ampere cell discharging at the rate of 5 amperes, an efficiency of 80 per cent. might be obtained, but on increasing the current to 40 amperes, the output falls to less than 50 per cent., for when the rate of discharge is high, the E.M.F. falls rapidly. It is highly important that the connections between the cells and to the external circuit should be well and substantially made. The average internal resistance of a cell containing 31 L-plates is but 0·001ʷ, and it is therefore very easy to incur even a greater loss in the connections of a battery than in the battery itself. Such losses further reduce the efficiency of the battery.

It remains now to consider the general utility and application of secondary cells, which may be classed under three heads, viz. storage, regulation, and distribution.

As a means of storing energy to be afterwards converted into a current of electricity, the secondary battery stands alone. It is often compared to a domestic water-cistern, but the analogy is not a very happy one, for the cistern receives a periodical heavy charge of water to be delivered in small or large quantities as required, while the battery usually receives its charge gradually or even intermittently as opportunities arise, whereas its rate of discharge often approaches the highest possible, and frequently exceeds the charging rate, when, of course, the duration of the discharge is considerably shorter than that of the charge. Again, a secondary battery cannot be charged and discharged simultaneously as can a water-cistern, that is to say a current can only pass through the cell at any particular moment in one direction —charge or discharge.

As the secondary cell has a working electro-motive force of but two volts, as its capacity (as compared with its weight) is very small, and as its practical efficiency is very low, it is in many cases impracticable to employ such apparatus at a supply station to

meet even the small demand during the daytime, although the secondary battery is growing in favour as a stand-by. But its more general utility for central-station work is to assist the dynamos in meeting the maximum demand. It will readily be seen that in ordinary commercial work there is a brief period in the evening, particularly in winter, when the demand for lighting current rapidly increases and quite as rapidly falls. In order to meet these requirements by means of direct generators a large increase in boilers, engines, and dynamos would be involved; but where secondary batteries are employed, the spare current in the daytime, when the load is usually very light, can be employed to charge the secondary cells, and it then happens that although the efficiency may be only 50 per cent., a real economy is effected by utilising them for supplying the 'peak' or top loads. Similarly in the smaller tramway installations, where only a few cars are in use, and where, therefore, average contingencies cannot be assumed, there are occasions when the cars are starting from rest or when they are mounting heavy gradients, and in such cases secondary cells are useful for meeting the brief heavy demands. Even in the larger stations secondary batteries offer considerable advantages in the morning and evening, when the demand is exceptionally heavy for a short period. It would undoubtedly be a great advantage if secondary batteries could be economically constructed and maintained of sufficiently large dimensions to have a capacity to meet, say, one complete day's supply. In that case an electric-lighting or power station would be placed on a basis more nearly approaching that of an ordinary gas-works. The generating plant required by the station would thereby be considerably reduced, the risk of a fall in the pressure when a sudden demand arises would be obviated, and the working expenses would be lessened.

Although, however, the secondary battery is hardly likely to take a front place in public supply works, it offers very many advantages for comparatively small or private installations. In such cases direct-current working is the rule; but it is rarely desired to keep the generating plant—that is to say, the engine and dynamo—running day and night, but rather to run it only during the hours when the load is heavy, and to trust to the

secondary battery to supply the required current at other times.

Secondary cells have also the advantage in small stations that, where they are of sufficient capacity to maintain the ordinary number of lamps, they can, on emergency, be employed to increase considerably the total amount of current supplied. For example, suppose the dynamo to be able to generate the same amount of current as the secondaries can discharge, the latter can be charged during the day, and both dynamo and battery employed either independently or together for lighting-purposes in the evening.

Many other instances where the storage capacity of secondary cells is of great value will probably suggest themselves to the student. There is, however, one class of work in which the secondary battery fulfils a function in a manner peculiar to itself, and that is in the propulsion of road vehicles and launches or other comparatively small vessels. Nothing can be more objectionable in such cases than the dirt, noise and smell attendant upon the employment of steam or petroleum, while it is almost impossible to conceive anything more clean, silent, and agreeable than a secondary battery placed in lead-lined teak boxes, stowed in the hold or under the seats, and charged as required from a generating plant situated in a convenient spot. A word of caution is, however, necessary, and that is that ample ventilation should always be afforded for the escape of the hydrogen and oxygen gases which are evolved during the charging, otherwise there will be some risk of an explosion.

Secondary batteries employed for the propulsion of tramcar and ordinary road vehicles should be arranged in trays, so that it is practicable to slide them in and out of the cars or carriages between the journeys. In many cases the battery is not removed, but the vehicle is taken to the charging station and the battery is then charged in position. Propulsion by means of secondary batteries has so far met with but limited success, chiefly on account of the comparatively low efficiency of secondary batteries, their great weight and the cost of wear and tear. These are the points to which attention is at present being directed, and with the improvements which are gradually being effected in

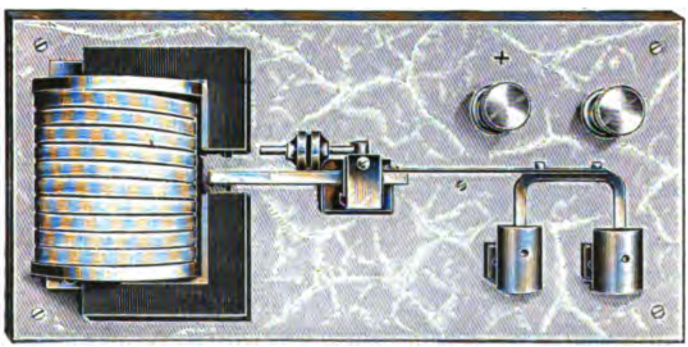
these directions, it is not improbable that there will be a substantial increase in the application of secondary batteries to this class of work. It must be remembered that a car with a secondary battery and motor is perfectly self-contained, and in the case of tramway working there is no need for either the more or less unsightly overhead conductor, or the much more expensive underground conductor built into a conduit running between, and parallel with, the rails. These systems, it will be remembered, were dealt with in Chapter XII.

A secondary battery is pre-eminently serviceable as a regulator for maintaining a uniform potential difference, more particularly in cases where the dynamo is driven by a gas or oil engine, and where, in consequence of the irregular and comparatively infrequent impulses imparted to the driving wheel, the potential difference developed by the machine is liable to considerable variations. Let it be supposed, for example, that a shunt-wound dynamo is employed, with the aid of a secondary battery, to supply current to a number of lamps joined up in parallel. Let the lamps be made to take a pressure of 100 volts, and let it be supposed for the moment that the battery has been charged to a pressure of 102 volts, and that the dynamo at each impulse of the engine develops for a moment 110 volts. Between these impulses the dynamo pressure may fall, and when an explosion is 'missed' it may even fall, in the absence of the battery, below 100 volts. The battery, however, tends to correct these irregularities. Should the electro-motive force of the dynamo fall below that of the battery, the latter will augment the current through the field-magnet of the former, and the strength of the field will therefore be increased, and, the current in the armature being at the same time diminished, the speed of the engine will be accelerated and a higher E.M.F. developed. The battery will at the same time maintain the proper voltage at the lamp terminals. On the other hand, the pressure of 110 volts obtained at the moment of the impulse will be too high for the lamps, but in that case the cells form a low resistance shunt to the lamp circuit, and they take up or absorb the superfluous volts, a strong current being urged through them and increasing their charge.

In some cases, more particularly where constant attendance

is not provided, an automatic switch is employed, which, in the event of the dynamo pressure falling materially, cuts out the machine and causes the circuit to be fed from the battery alone. It is quite conceivable that the driving belt might break, or the supply of gas for the engine be accidentally cut off, and in such cases the dynamo pressure would, of course, fall at once, with the result that, unless the dynamo promptly responded and continued to run as a motor, the battery would send such a strong current through the low-resistance armature as would suffice to burn it up. There are several automatic switches designed for preventing a disaster of this sort, one of them, the 'Nevile' auto-

FIG. 311



matic switch, being illustrated in fig. 311. It consists of an electro-magnet, with projecting pole-pieces bent over so as nearly to meet. Between them there is a balanced permanent steel magnet which can rock horizontally. To the further end of the magnet is attached a non-magnetic rod, which carries a copper fork. The electro-magnet is in the main charging circuit, and the pole-pieces are magnetised one way or the other, according to the direction of the current. If the dynamo pressure falls, the current passes from the battery to the machine, and makes the polarity of the lower pole-piece opposite to that of the adjacent end of the magnet, which is consequently drawn down, the copper fork being thereby raised, and, breaking contact with the mercury

contained in the cups beneath it, the charging circuit is thereby disconnected. When the dynamo pressure exceeds that of the battery, the direction of the current through the electro-magnet—and, therefore, the polarisation of the pole-pieces—are reversed. Consequently, the magnet is drawn up, the fork dipping again into the mercury, and re-making the charging circuit. Mercury switches are objectionable where the potential difference at the moment of disconnection is considerable, but in this case the switch can be adjusted so as to act when the difference between the pressure of the dynamo and that of the battery is very low, and in that case the spark caused by the breaking of the circuit would be small. There is a balance weight which can be seen in the figure immediately over the permanent magnet, and this weight can be so adjusted that the switch shall be actuated when the electro-motive force of the generator falls or rises to within 1 or 2 per cent. of the electro-motive force of the battery.

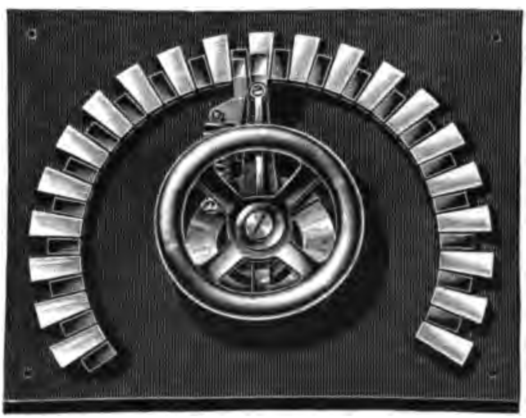
Another useful piece of apparatus is an automatic alarum, the object of which is to indicate when an excessively high current is being drawn from the cells. In one of these alarums a vertically fixed solenoid, consisting of a few turns of thick wire, is placed in the main circuit. When the current exceeds a certain prescribed limit, the soft iron core is attracted, and a horizontal spring attached to it completes a local circuit, causing one of the cells to send a current through an ordinary electric trembler bell.

In addition to these, there are many other pieces of apparatus, ingenious in their way and useful for special purposes, which, however, we need scarcely describe.

The use of a regulator switch, such as that illustrated in fig. 312, should, however, be understood. It will be remembered that the working pressure of a secondary battery ranges from 1·9 to 2·4 volts per cell. If, therefore, a pressure of 100 volts has to be maintained, a battery of 53 cells will, when their pressure has fallen to 1·9 each, be required. But 53 cells when fully charged would have an electro-motive force of nearly 135 volts. Hence the dynamo must be capable of developing this potential difference. If, however, the whole of the fully charged cells were to be joined direct to the lamps, the result would be that in a comparatively short time they would all break. It follows, therefore, that a

regulating switch is necessary, by the use of which the number of cells being charged and the number feeding the lamps may be independently varied. In the switch illustrated there is a movable arm connected to, say, the positive terminal of the charging dynamo, which can be turned by rotating the handle. This handle is in the form of a substantial metal ring. The contact brush at the end of the arm is laminated or composed of a number of strips of thin hard copper. The cells near the positive end of the battery are connected one to each of the brass or copper studs over which the arm travels. If we suppose

FIG. 312



the end cell to be joined to the left-hand stud, then when the arm rests on that stud the full battery is under charge. As the electromotive force of the battery rises the arm is moved from stud to stud, thus reducing the battery cell by cell as the charge increases. As will be seen from the figure, blocks of insulating material are fixed between the contact studs in order that the brush shall have an even course and not be able to drop in between the studs. When large cells are used, the switch arm is divided in the direction of its length into two parts, the distance between them being such that the forward part shall, in moving, make contact with, say, the second stud before the following part leaves the

first stud, and a resistance coil is in circuit between the two parts of the arm in order to prevent the cell being short-circuited and an unduly heavy current being thereby sent from stud to stud across the brush. Where this arrangement is not adopted the distance between the studs should be greater than the width of the brush, with the result that there is a momentary disconnection as the brush passes from stud to stud. The switches are made in varying sizes, according to the number of cells required to be switched out.

A similar switch is required between the battery and the lamp circuit. The number of cells to be cut out varies, of course, with their electro-motive force. When, for example, the cells of the battery referred to on page 642 are charged up to a pressure of 2·4 volts per cell, then 42 cells will suffice to maintain the lamp-pressure, the other 14 being cut out. The cells in use vary, therefore, from 42 to 53, according to their condition. A switch with fourteen studs is consequently required. The negative pole of the dynamo should be joined to the negative pole of the battery and the negative conductor of the lamp circuit. It will be noticed that the number of cells required to feed the lamps must always be increased when the dynamo is disconnected. This arises from two causes—first, that the electro-motive force of a secondary cell falls immediately the charging current is switched off, and secondly, that the potential difference obtained from any portion of a battery, which is, at the same time, receiving a charge, is made up of two parts—viz. the electro-motive force of the battery itself plus that part of the impressed electro-motive force which has to be applied in order to make up for the fall of potential in overcoming the battery resistance.

CHAPTER XV

ARC LAMPS

In this and the following chapter we have to deal with the question of illumination, and it must be borne in mind that illumination is the whole object of lighting, so that it is very essential that the student should be careful to discriminate between the amount of light developed by any particular source and the resulting illumination—that is to say, the relative effectiveness with which that light is distributed and utilised. It would be a grand achievement if we could by artificial means approach ordinary sunlight in quality, in quantity, or even in uniformity of distribution. This, however, we cannot hope to do. The light emitted by an arc lamp actually approaches in quality more nearly to the solar luminous rays than does that of any other artificial illuminant, although the light of the arc itself contains in reality a larger proportion of orange or yellow rays than does the light of the sun, and if examined on a grey day when there are no colour contrasts about, the 'light shed by tolerably good arc lamps with tolerably good carbons is of a pale primrose or straw colour.' This is in direct opposition to the generally prevalent idea that the arc light is bluish and even violet, but the illusion arises from the fact that people rarely see an arc lamp burning except at night-time, and as they have always been accustomed to the decidedly yellow gas, oil, or candle light, they naturally by comparison consider the arc blue. Obviously the fact of the lamp being used at night cannot alter the colour of the light emitted. If, however, the carbons be impure there is usually a blue or purple tinge which may be due to the absorption of yellow rays by the film or mist of incandescent particles which surrounds an ordinary arc. In the arc, therefore, the approximation in quality to solar light is very close.

It is a remarkable fact that until about the year 1881 electric lighting was, except in the laboratory, only performed by the agency of the electric arc, a development of the classical experiment made by Davy about a hundred years ago, when he employed 2000 primary cells of a very crude type, which he connected to two pieces of light wood-charcoal about an inch long and one-sixth of an inch in diameter. When these 'were brought near each other (within the thirtieth or fortieth part of an inch) a bright spark was produced, and more than half the volume of the charcoal became ignited to whiteness; and, by withdrawing the points from each other, a constant discharge took place through the heated air in a space equal at least to four inches, producing a most brilliant ascending arch of light, broad and conical in form in the middle.' When any substance was introduced into the arch or arc so produced, 'it became incandescent; platinum melted like wax in the flame of a candle; sapphire, magnesia, lime, and the most refractory substances were fused. Fragments of diamond and granite rapidly disappeared without undergoing any previous fusion.' The arched form taken by the luminous particles of carbon resulted from the upward rush of the subjacent heated air. Were the carbons placed vertically, instead of horizontally, the particles would be disposed differently, and bear little or no resemblance to an arch. The term arch, in its abbreviated form, arc, is, however, retained as the name of the luminous space between the carbons.

The electric arc can be produced by placing in electrical contact two rods of carbon, either of the gas retort or of the prepared type, and, after applying to them a potential difference of about 45 volts, drawing them apart for a short distance. Such a potential difference is altogether inadequate to cause a spark to dart across even the shortest measurable air space. When, however, these rods are made to touch, a current is initiated, and, the resistance at the point of contact being somewhat considerable, there is a corresponding amount of heat developed at that point. If the carbons are kept together the contact surfaces will become more or less incandescent, although the amount of light emitted will be relatively small, the heated surfaces each serving as a screen to intercept the light of the other. If we, however,

separate the carbons, either by automatic or by other means, molecular disintegration and volatilisation of the carbon take place, and the air space is impregnated with so great a quantity of carbon particles raised by the current to a state of incandescence that the resistance of the space is so far reduced as to allow the current to be maintained by a comparatively feeble electro-motive force. The distance to which the carbons can be separated without breaking the arc, and thereby disconnecting the circuit, depends upon the E.M.F. available, and can therefore, within certain limits, be increased by increasing the number of cells, or the potential difference at the dynamo terminals, but with an E.M.F. of about 50 volts at the lamp terminals the length of the arc should, in order to give the best results, be limited to three or four millimetres.

The maintenance of the ends of the carbon rods in a state of incandescence involves a continual disintegrating effect upon the carbons, as well as a certain amount of consumption by ordinary combustion, some of the particles uniting chemically with the constituents of the atmosphere. The products of combustion are, however, very much smaller in quantity, and therefore less harmful, than those derived from a corresponding gas, oil, or candle flame. The two rods are not, with a continuous or direct current, consumed at equal rates, the consumption of the rod connected to the positive pole of the dynamo or battery—and called, therefore, the positive carbon—being approximately twice as much as that of the other or negative carbon; when an alternating current is employed the consumption of both carbons is practically the same, because each becomes in turn the positive.

An arc lamp is an important piece of apparatus, which carries two rods of carbon, which, before the passage of the current, are placed in contact, but which the current itself in passing must separate, and simultaneously set up between them a path of low resistance, so that the current can continue to flow, and render the ends of the rods incandescent. But in order to maintain the arc it is also essential that some device should be provided for 'feeding' the carbons together, at a rate proportionate to their consumption. It is obvious that in order to maintain this cycle of changes a greater or less amount of mechanism is necessary.

Before, however, we can study this mechanism, some attention must be bestowed upon one or two other important considerations.

One very interesting and striking feature is the difference of formation given to the carbon rods. In the majority of cases arc lamps are maintained by direct or continuous currents, and in such cases it is observed that the end of the positive rod, whatever may be its initial shape or form, becomes in a short time (see fig. 313) worn down to a somewhat conical form. The apex of the cone is, however, absent, the extreme end of the carbon being hollowed out so as to form a kind of crater; and it is in the hollow of this crater that the most intense heat is developed, constituting it, therefore, the chief source of light. The negative rod is gradually consumed until its extremity is of a fairly true conical shape, but somewhat sharper than the positive carbon, and it is interesting to observe that some of the particles of which the positive rod is denuded are condensed upon the surface of the negative rod. If, after being allowed to burn for a sufficient time so as to form a crater at the end of the positive carbon, the direction of the current were reversed, this crater would be gradually destroyed and another formed on the other carbon. We can readily understand, therefore, that when the current rapidly alternates in direction both the carbons will be similarly tapered, and that on neither of them will a definite crater be formed.

FIG. 313

If the hot crater of a direct-current arc is examined through a sheet of blue glass it will readily be seen that it is by far the most intensely luminous (and therefore the most intensely heated) portion of the arc. So great is the difference between the temperatures of the two carbons, that while the negative ceases to be luminous almost immediately after the current has been switched off, the positive in the region of the crater remains

white or red hot for an appreciable time. When this carbon has cooled down so that it may be handled without inconvenience, it will be seen that the crater is not only very clearly defined, but that its surface presents a smooth and somewhat metallic appearance, and would seem to warrant the assumption that the exceedingly obdurate carbon, which has never been seen in the liquid state, has been actually fused and re-solidified.

It has been estimated that while 85 per cent. of the light is derived from the positive carbon, only 10 per cent. comes from the negative carbon, the remaining 5 per cent. being attributed to the 'flame,' or the illuminated particles between the two carbons. These figures are only true for a certain pair of carbons burning under certain conditions, but they are sufficiently accurate for general purposes, and some rough idea of the relative thermal intensities of the various parts of the arc may be gathered from them. It is not altogether unusual to speak of the temperature attained by the negative carbon as being largely due to its undergoing a 'roasting' process in front of the positive carbon, but this is evidently not quite correct, for the temperature attained by the negative carbon is in reality very high, and is largely due to the accretion of white-hot carbon particles which are precipitated upon it from the crater. The actual temperature attained by the two carbons is to some extent a matter of conjecture. If carbon had ever, in any other circumstances, been liquefied or volatilised, the question would have been rendered much easier, for then we should in all probability have known the temperature at which the change from the solid or liquid state takes place, and we should therefore have known the limiting temperature to which the crater of the positive carbon could be raised. We shall have occasion to refer again to this point, but it may here be observed that experiment would appear to indicate that the temperature attained by the positive carbon is about 3500° C., the temperature of the negative being somewhere between 2100° and 2500° C.

It is, as will be more evident presently, a matter of some importance that if, on different occasions, a carbon rod were raised to the same luminosity, it would be at the same temperature; and, *vice versâ*, if it were raised to the same temperature on

different occasions, the light emitted in each case would be of the same intensity.

For the sake of those of our readers who are not acquainted with the character of a beam of light a few words on the subject may not be out of place. Pure white light is in reality composed of rays of seven different colours superposed upon one another, or blended together. These colours are red, orange, yellow, green, blue, indigo, and violet, and it is by the simultaneous reception of these rays, in certain definite proportions, by the optic nerves that the sensation of white light is conveyed to the brain. The generally accepted theory, which endeavours to explain the manner in which a beam of light is propagated, is based on the assumption that all interstellar space, and likewise the space between the minute particles of all material bodies, is pervaded by that mysterious medium already referred to as ether.

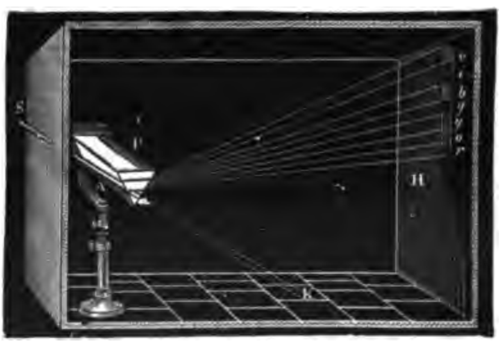
A body may be said to be a luminous substance when it is a source of light-rays, such as the sun or a candle-flame. Now the luminosity of a body is ascribed to an almost infinitely rapid vibration of its molecules; this vibratory motion is communicated to the ether particles pervading and enveloping the substance, and is propagated in all directions in the form of spherical wave-motions. The colour of the ray varies with or is determined by the rate of vibration.

If a beam of solar light (S, fig. 314) is allowed to pass through a hole in the shutter or wall of an otherwise absolutely dark room, it will illuminate a small section of the floor, K, but if a prism or wedge-shaped piece of glass, P, is placed in the track of the beam of light, after the manner shown in the diagram, the beam will be diverted or 'refracted' and the rays separated; on emerging and being allowed to fall upon the screen, H, or even on the wall of the room, the beam will be found to consist of the seven colours above enumerated. This many-coloured band of light is generally referred to as the spectrum. The velocity with which light travels is about 186,000 miles per second, and it has been calculated that the length of a wave of the extreme red end of the spectrum (that is to say, of a luminous ray having the lowest rate of vibration) is such that 39,000 such waves, placed end to end, would cover only one inch, while 64,631 of the

extreme violet waves would be required to span the same distance. It follows that in one second, 464 millions of millions of red waves, and 678 millions of millions of violet waves, enter the eye and strike the optic nerves.

If a beam be not of a pure white colour, the impurity or irregularity may be due to the chemical constitution of the source of light, or to varying degrees of luminosity. For example, if a beam from a red-hot substance is allowed to fall upon the prism referred to above, the decomposition or separation of the rays will not result in the formation of the seven coloured bands, those near the violet end of the spectrum being absent on account of the vibrations being insufficiently rapid to produce

FIG. 314

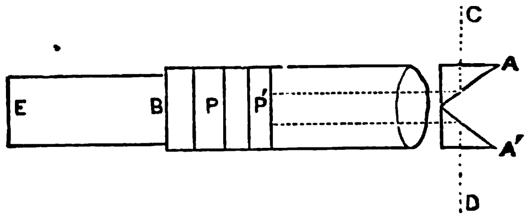


them. When a source of light is heated to different degrees of luminosity, the spectra resulting therefrom will consequently vary, while, on the other hand, if it is raised at different times to the same temperature, and therefore to the same degree of luminosity, the spectra obtained will be the same in every case.

A very simple piece of apparatus, called the 'horizontal slit' photometer, has been devised by Dr. Nichols for the purpose of facilitating the simultaneous study of the spectra from two separate sources of light. The instrument is illustrated in fig. 315. It consists of a direct-vision spectroscope (an instrument for observing spectra) with a horizontal slit. Immediately in front of the slit

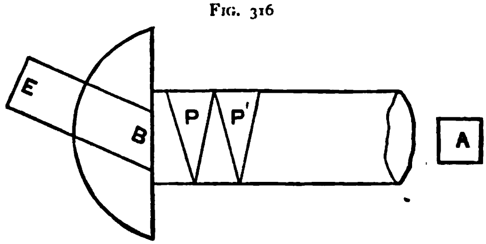
are two 'totally reflecting' prisms A, A′. The shape of these prisms is such that the rays from the lamps situate, say, at C and D, instead of passing straight through, are entirely reflected from the inclined faces, the angle which the reflected rays make with these faces being, in accordance with the accepted law, equal to that made by the incident rays. The direction of the two sets of rays

FIG. 315



is indicated in the figure by the dotted lines. The rays after passing through the slit traverse the dispersing or analysing prisms P, P′, where they are decomposed into their several component colours, and the two spectra are projected side by side, and can be viewed together through the eye-piece E, which is furnished for the purpose with a horizontal cross wire and a diaphragm

FIG. 316



with a narrow rectangular opening. This eye-piece, together with the first joint of the telescope arrangement, is movable about B, the centre of a graduated semicircle, as shown in fig. 316, which is a diagrammatic view taken at an angle of 90° with that shown in fig. 315. Thus the whole range of the spectra can be very conveniently studied.

Now it has been ascertained that the spectra of the light emitted by the incandescent crater of a pure carbon rod are always the same, that in fact the same proportion between the various coloured bands is always evidenced, whence it is deduced that the temperature of that portion of the fully developed arc is always raised to the same point. This constitutes one great reason for accepting the proposition that the true arc is attained when there is a volatilisation of the carbon; for, so far as experiment has hitherto led us, there is for a given material a constant critical point of temperature at which a change from the solid to the liquid or to the gaseous state ensues, and, the most important point of all, this temperature is not any further increased until the whole of the solid body has been so changed. The admixture with the carbon of any foreign body (all such bodies having a lower critical temperature than carbon) lowers the temperature at which volatilisation ensues, and therefore reduces the luminosity of the crater. Moreover, when a body is transformed from the solid to the liquid or gaseous state, a certain amount of heat, known as the latent heat, is absorbed in the process. Thus one pound of ice at the freezing temperature absorbs about as much heat during its conversion into water at the same temperature as would suffice to raise the same mass of water from the freezing temperature to 80° C.; whence the latent heat of water is said to be 80° C. On the other hand, when a liquid is solidified a corresponding amount of heat is given out during the change. Thus one pound of water at the freezing temperature in being converted into ice gives out as much heat as would raise the temperature of the same mass to 80° C.

Again, if we apply heat to water contained in an open vessel it will be found impossible to raise the temperature above 100° C., any further heat being rendered latent in the steam which escapes. The steam on resuming the liquid state will give up this latent heat. Similarly with the electric arc. There is considerable electrical resistance at the surface of the carbons, the ends of which are, therefore, on being separated, raised to almost a white heat, and, the current being maintained, the temperature of the positive carbon is further raised until the temperature of volatilisation is reached. The vapour consequently absorbs a considerable

amount of energy, yielding it up again on re-solidification. The essential point to be noticed is that, the temperature of volatilisation having been once attained, no further increase can be made: that is to say, the temperature at which the physical change from the solid to the gaseous state takes place is the limiting temperature to which the carbon can be raised. This means that there is a limit to the intensity of the light which a given pair of carbons can be made to yield. The student must carefully discriminate between the luminous intensity—or, as it is more generally called, the 'intrinsic brilliance'—of the arc, and the quantity of luminous rays which the arc can develop. By the intrinsic brilliance is meant the quantity of light or of luminous rays emitted per square millimetre of crater, and it is this intrinsic brilliance which is limited by the temperature of volatilisation. The total quantity of light emitted by an arc is the product of this intrinsic brilliance into the area of the crater, and it is important to remember that, when the temperature of volatilisation has been reached, any further augmentation in the strength of the current results in an increase in the area of the crater, and there is, of course, a proportional increase in the quantity of light emitted. This fact is confirmed by the experiments of M. Violle, who showed that the intrinsic brilliance of the crater remains sensibly constant when the power supplied is raised through a range of 1 to 60, and he also found the intrinsic brilliance of the crater identical for all carbon arcs. The measurements taken in various parts of the spectrum and the photographs obtained 'left no doubt whatever on this point.' The power supplied to the arcs with which he experimented ranged from 10 amperes at 50 volts up to 400 amperes at 85 volts, and it was in this series of experiments that the temperature of volatilisation was estimated to be not less than 3500° C. The intrinsic brilliance of a fully developed arc has not yet been definitely determined, but has been estimated by various authorities at values ranging from 146 to 170, or an average of 158 candle-power per square millimetre of crater area. According to M. Blondel, who has worked assiduously in striving to solve many of the problems in arc lighting, the intrinsic brilliance of carbon at 3500° C. is 8000 times as great as that of platinum at 1775° C.

The positive carbon being made hotter than the negative, but yet not exceeding a certain maximum, warrants the assumption that the negative is never volatilised, and that any diminution in size which the latter may suffer must arise from simple combustion consequent upon the combination of the red-hot carbon with atmospheric oxygen. But as there is no free oxygen in the track of the current—that is, along the line joining the two carbons—the combustion takes place around the outer surfaces of the carbon, and this accounts in a great measure for the conical shape assumed by it. To a similar action must also be ascribed the partial tapering of the positive carbon.

Accepting the theory that the carbon is gradually volatilised in the crater, and that there is a certain definite temperature at which this volatilisation takes place, there is also involved the necessity for the expenditure of a certain definite minimum amount of energy in order that these changes may be brought about. It has been observed that, in order to maintain a properly developed arc, a potential difference of about 44 volts between the two carbons is necessary, and it has also been demonstrated by joining a voltmeter on the one side to the positive carbon rod, and on the other to a carbon pencil inserted horizontally in the arc between the rods, that 38 or 39 volts are lost or expended at or near the surface of the crater, the remaining 5 or 6 volts sufficing to maintain the current through the carbon and other vapours between the two rods. Several explanations of this sudden fall of potential at the crater have been attempted. One of them is that the phenomenon is due simply to the contact resistance between the carbon and the air or vapour adjacent to it, but if this were accepted it would be difficult to account for the absence of a corresponding resistance at the surface of the negative carbon. It is far more likely that the fall is due directly to the volatilisation of the carbon, and that the volts absorbed afford a measure of the energy required in overcoming the molecular attractions or cohesive force of the carbon particles. It has been suggested that these reactions result in the establishment of a counter electromotive force in the arc, between the carbon vapour and the positive rod, amounting to nearly 39 volts. When, however, the current is switched off, no evidence is obtainable of the existence

of any appreciable back E.M.F. between the carbons. The gases between the rods speedily get cool or even displaced, and consequently the carbons are separated by an almost perfect insulator, and, the electrical condition of the carbon vapour being a paramount factor in the question, it follows that the only free portions of such electricity as would flow, did circumstances permit, would be those existing on the electrodes, and these are in any case very trifling. If we were able by some means other than the arc itself to have the two carbons raised to and maintained at temperatures such as they attain in the arc, we might perhaps obtain some direct proof of the existence or otherwise of this back E.M.F.

The whole question of the existence or otherwise of a counter electro-motive force is, therefore, still shrouded in doubt; but this much is certain, that there is in a properly developed arc a fall of potential in the immediate neighbourhood of the crater of about 39 volts, and this fall is independent of the length of the arc, of the area of the crater, and of the true or ohmic resistance of the various parts of the circuit. It is an interesting fact, and one which has given rise to many different conjectures, that the *apparent* resistance of the arc does not increase proportionally with the distance between the rods. The resistance of an arc of 6 millimetres, for example, is nothing like double that of an arc of 3 millimetres. If, for example, a reference be made to fig. 319 (page 662) it will be seen that a 3-millimetre arc can be maintained with a potential difference of about 48 volts and a current of 12 amperes, so that the resistance between the points at which the voltmeter terminals are applied is $\frac{48}{12} = 4^{\omega}$. Similarly, a 6-millimetre arc can be maintained when the potential difference is about 57·5 volts and the current 12 amperes, or an apparent resistance of $\frac{57 \cdot 5}{12} = 4 \cdot 8^{\omega}$. It is thus shown that although the length of the arc is doubled, the increase in its resistance is only about 20 per cent. But this is only what should be expected if the theory of volatilisation of the positive carbon is correct, for, however long the arc may be, the volatilisation can only take place in the crater. If the resistance of the air-space, with its impregnation of carbon particles, were the only element entering into the

question, the resistances in the two cases instanced should be as two to one. But the experiments which have been made with arcs of different lengths (the electro-motive force being also varied so as to keep the current strength constant) have shown that if we allow for a definite fall of 39 volts at the crater there remains a resistance which varies proportionally with the length of the arc, and which affords thereby a demonstration of the actual existence of a sudden drop at this point, which might be due either to the development and maintenance of a counter E.M.F., to the energy absorbed by the carbon in volatilising, or, as Mrs. Ayrton has suggested, to the work done in overcoming the resistance of a thin film of carbon vapour in intimate contact with the surface of the crater and separating it from the remainder of the arc. It is difficult to resist the weight of evidence in favour of the volatilisation hypothesis. If the student turns again to the experiments with the 3-millimetre and 6-millimetre arcs, and deducts from the potential differences the 39 volts attributed to the volatilisation process, the resistance in the former case becomes $\frac{48-39}{12} = 0.75^{\omega}$ and in the latter $\frac{57.5-39}{12} = 1.54^{\omega}$, or practically 1 : 2.

The great practical lesson to be derived from a knowledge of this effect, however, is that the potential difference which is applied to the lamp must always exceed 39 volts, or it will fail to maintain the arc. It is, in fact, usual to provide on a direct current circuit a potential difference of about 50 volts for each lamp; the actual or true resistance of the air-space separating the carbons when they are in the normal position for lighting, say at a distance of about 3 millimetres apart, being variously estimated at something between one-fifth and one-half of an ohm.

When the potential difference between the carbons falls below 40 volts a steady arc cannot be maintained, and the carbons rise and fall (or 'pump') vigorously—that is to say, the current with the carbons in contact is, consequent upon the reduced resistance, heavy, and the carbons accordingly separate and strike the arc; but the feeble electro-motive force provided is incompetent to cause the all-important volatilisation of the carbon, and the path for the current is wanting in the required amount of carbon vapour.

As a consequence, the carbons feed forward rapidly, to be again jerked apart, and, these reactions being continued, we have a variable and unsteady arc. In these circumstances no true crater is completely formed; there is no true volatilisation, and neither of the carbons is raised to its limiting temperature. They are rendered only feebly incandescent, and comparatively little light is emitted. There is a peculiar phenomenon which frequently accompanies an unsteady arc, which is known, from the noise emitted, as hissing. It has been demonstrated by Mrs. Ayrton that this effect is due to an abnormal enlargement of the crater and a consequent accession of oxygen to the volatilising carbon. So long as the crater is confined within the limits of the end of the positive carbon the arc is silent, but if from any cause the current

FIG. 317

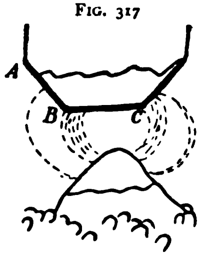
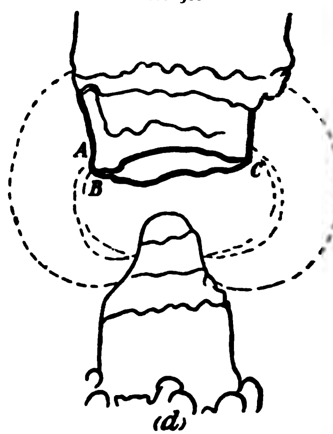


FIG. 318



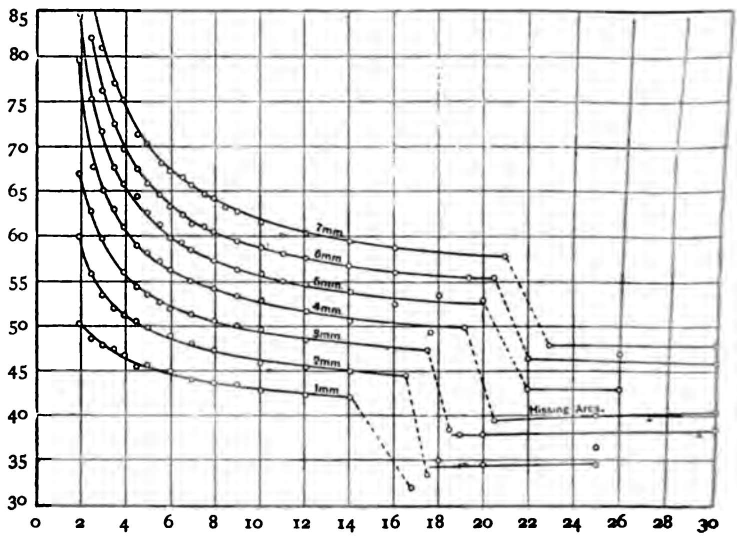
is so far increased that the crater has no alternative but to exceed those limits, and extend up the side of the rod (in order that the required crater area may be provided), the air, that is to say oxygen, will be brought into contact with the crater, and the arc will hiss. Figs. 317 and 318, which are reproduced from Mrs. Ayrton's work on the electric arc, will perhaps make this clearer. Fig. 317 is a representation of the ends of the solid carbon rods of 11 millimetres diameter for the positive and 9 millimetres for the negative when a current of 6 amperes is allowed to flow. It will be seen that the area of the crater B C is well within the limits of the diameter of the carbon, and that the conical

tip is well formed; a silent arc, therefore, results. In the experiment illustrated in fig. 318 the same carbons were used, and the length of the arc was the same as in the former case, but the current was increased five-fold, that is to 30 amperes. The area of the crater represented by B C is much greater, and has, in fact, extended up the side of the carbon towards A, and the result is that the peculiar hissing ensues. Moreover, the conical tip has disappeared, and the diameter of the end of the rod is very little less than that of the upper portion, and Mrs. Ayrton has found that with a hissing arc it is quite the usual thing for the conical end to be consumed so that the crater occupies an area almost equal to the cross-section of the carbon, and is then compelled to creep up the almost vertical sides of the rod. It thus becomes easy for the atmospheric oxygen to have access to the crater, and to cause the chemical combustion of the carbon which results in hissing. A hissing arc is also usually accompanied by a tall mushroom growth on the tip of the negative carbon, consequent upon a copious discharge of carbon particles from the positive rod. One very interesting feature is that just as the hissing commences there is a distinct fall of something like 10 volts in the potential difference between the carbons, that the current also rises in strength to the extent of 2 or 3 amperes, and that if the current be still further increased the hissing is maintained, while there is only a fractional rise in the potential difference. Fig. 319 shows the results of a large number of tests which were made between a pair of solid carbons of 11 millimetres diameter for the positive, and 9 millimetres for the negative. The current was gradually increased from 2 to 30 amperes, and the length of the arc, or the distance between the carbons, varied from 1 millimetre to 7 millimetres. The small circles indicate the several points at which measurements were taken. The dotted lines indicate the unstable conditions where the point of the positive carbon has been consumed and the area of the crater has begun to extend up the side of the carbon. After this extension and the potential difference has fallen a matter of ten volts, hissing is maintained under a steady potential difference although the current may be increased considerably. The passage from the steady to the hissing stage is very sudden, and it is interesting to note that the greater the length of the arc, the greater is the

current which can be maintained without the risk of passing the critical point and setting up hissing.

Letting it be granted that the minimum potential difference required is determined by the temperature of volatilisation, it should be evident that a smaller difference would be sufficient to maintain a given current between any pair of rods, such as iron, copper, or zinc, which have a lower 'boiling-point' (or temperature of volatilisation) than carbon, and that, as a correspondingly

FIG. 319



smaller amount of energy is absorbed, the intensity of the light emitted, or the intrinsic brilliance of the arc, should be reduced.

We have, as a matter of fact, demonstrated this point experimentally; for example, two arc lamps were placed in series so that the same current was maintained through them, but one of the lamps had carbon rods, while the other had iron rods of similar dimensions. The illuminating powers were then compared by placing the lamps on opposite sides of the disc of a Hartley's Bunsen photometer. The potential differences absorbed by the

respective pairs of rods were measured simultaneously, and it was found, for example, that with a current of 10 amperes and arcs of equal length the carbons absorbed 57 volts, while the iron rods took only 27 volts. A few of the results are appended :—

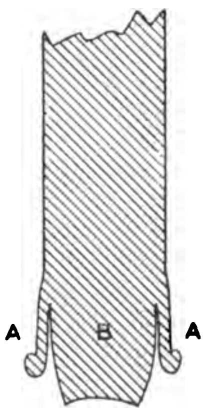
Current in Amperes	Volts between ends of rods		Distances in centimetres from photometer disc	
	Carbon	Iron	Carbon	Iron
10	57	27	65	32
8·5	55	26	64	31
7·5	53	25	63	30
		Averages		
8·6	55	26	64	31

In each case the arcs were of equal length, about $\frac{3}{16}$ inch. The iron used was soft, and of the same diameter as the carbon. It is interesting to notice that no spluttering was observed in the iron arc after the current became steady, and it will be seen that the potential difference required by the iron arc was only about half that necessary for the ordinary carbon arc, while the illumination was only about one-fourth, as evidenced by the fact that the average distance of the carbon from the photometer disc was twice that of the iron, clearly showing that the electrode with the higher boiling-point required a higher electro-motive force, and that as the temperature of the electrodes was increased the efficiency of the lamp was enhanced.

Similar experiments were performed with rods of copper, brass, and other metals in place of the carbon, but they all told the same tale—namely, that the required electro-motive force depends upon the volatilisation temperature or boiling-point of the material of which the electrodes were composed. The experiment with zinc rods was highly entertaining. They spluttered and guttered considerably, although a fairly steady arc was capable of being maintained for a short time. Occasionally the upper rod would penetrate some distance into the lower, the centre of which simply resolved itself into a mass of molten metal encased in a solid tube, which would ultimately give way some distance down the rod and allow the molten zinc to run out.

An arc lamp has recently been devised, known as the 'Magnetite' lamp, in which the positive rod is of copper while the negative consists of a mixture of black oxide of iron and certain chromium salts. It is said that the lamp is efficient and effective, but there is not enough known about it to enable a definite opinion to be formed. As both rods volatilise at a comparatively low temperature, and as copper oxidises at a low temperature, it would appear that the intrinsic brilliance is of a low order and that atmospheric oxygen is prevented from having access to the arc. The character of the lamp is here referred to in order that the student may follow the trend of modern thought in such matters, and he will do well to remember this point when studying the latter portion of this chapter.

FIG. 320



When the distance between the carbons of an ordinary arc lamp is excessive the resistance becomes too great to allow a stable arc to be maintained, the end of the lower, or negative, carbon becomes less tapered or conical, and the arc flares and flickers, travelling from side to side across the carbons. There is then a considerable increase in the amount of chemical combustion going on, because the air necessary for combustion is more freely and more effectively supplied, with the result that the electrical efficiency is reduced and the illumination becomes very variable. When the distance is small the taper of the negative carbon is lengthened, and the illuminating power of the arc is reduced by each carbon acting as a screen for the other. This shortening of the arc is accompanied by a very imperfect crater, and it is only from a portion of this crater that the arc is at any one moment passing. The longer taper is attributed to a deposit of carbon particles from the positive rod. These particles are emitted under all conditions, but it is only when the carbon rods are close together, and consequently the number of particles is greatly increased, that a sufficient quantity reaches the negative carbon to form the extra tip. The taper of

the negative carbon is also lengthened as the current is increased. As we have already indicated, however, the taper in this case is mainly attributable to combustion of the carbon owing to a greater amount of it being raised to a sufficiently high temperature. When the carbons are too large the arc is liable to shift and get out of centre.

It has been pointed out by Mrs. Ayrton that the high temperature to which the inner portion of the positive carbon is raised causes the outer portion to expand and split, forming a sort of fringe which hangs down over the inner and hotter part from which it has broken away, as shown in fig. 320, where A A represent the fringe and B the solid carbon. 'Between this crust—which crumbles at a touch when cold—and the body of the carbon there is a space of from 0·5 millimetre to 1 millimetre, to the height of 5 millimetres or more, from which when the arc is burning sparks fly out, drop down to the edge of the crust, and then fly outwards and upwards, probably carried along by the strong upward draught of the column of hot carbon and air. . . . The tips of the strips of carbon that form the outer crust apparently get burnt by the hot volatile carbon into a semi-globular shape, and they boil and bubble under the action of this heat just as a lump of sugar does when held in a candle-flame.'

FIG. 321

The efficiency and reliability of an arc lamp depend very largely upon the quality of the carbons employed. When gas-retort or other irregular carbon is used, the impurities contained therein are fused and give rise to small nodular growths which, under a lens, or even a common magnifying-glass, impart to the rods a remarkable appearance, as illustrated in fig. 321. These nodular excrescences do not manifest themselves when properly prepared carbons are employed. Their very presence denotes a wasteful consumption of energy, for they imply that the impurities are, as

it were, sorted out from the other constituents of the electrodes; they are then concentrated and liquefied, and urged across the arc from one carbon to the other, without emitting that percentage of light rays which would arise were the energy they absorb expended on the carbon. As might have been gathered from what has already been said, these impurities also reduce the efficiency of the arc by hindering the carbon from attaining its maximum temperature.

When the carbons are very porous or wanting in density, the arc is usually lengthened, the carbon disintegrating readily and flaring considerably. With pieces of gas-coke an arc of some inches can be obtained.

The composition of and the method of preparing or manufacturing artificial carbons vary considerably, the precise details being in most cases regarded as trade secrets. Generally, however, graphite derived from gas-retort carbon forms the basis, this being ground up and intimately mixed with pure carbon powder derived from the destructive distillation of some such organic substances as gas-tar, pitch, or bitumen. An adhesive substance, such as a syrup of cane-sugar and gum, is then added to make a paste, the rods being shaped either by simply moulding or squeezing, or by forcing the mixture with considerable pressure through a die plate. The latter method is usually adopted in practice. The rods so formed are then baked in an oven a number of times, to decompose the carbonaceous compounds, and drive off the volatile constituents. Immersion in syrup usually takes place between the bakings. But great care is essential to remove any foreign substance from the ingredients, and so to ensure the production of a homogeneous rod.

The chief requirements which it is necessary that a carbon rod should fulfil are that it should be dense, that its molecular or mechanical structure should be uniform, that it should be pure, and that its electrical resistance should be low.

The resistance of prepared carbon varies with the different makers, the resistance of one specimen amounting to 2430 times that of a similar piece of pure copper, or nearly 4000 microhms per cubic centimetre. The specific resistance of the comparatively impure and more crystalline gas-retort carbon

has been found to be 17 times as great as that of the prepared material. The actual resistance of the prepared carbons ordinarily used for arc lamps is from 0·15 to 0·175 ohm per foot.

It is obvious that when long carbons are used it is important that the specific resistance should be as low as possible. The resistance of a pair of new or full-length carbons has an appreciable effect upon the total resistance of the lamp, and the reduction in resistance as the rods burn away tends, under a constant potential difference at the terminals, to increase unduly the strength of the resulting current.

Carbons are frequently 'cored.' There are two ways of doing this: the older process consists in first making the carbon in the form of a tube with a small hole or channel along the axis, and with thick sides, the channel being closed at one end. A solution of certain materials, containing in suspension a fine powder of the same nature as the carbon rod, is then introduced at the free end under high pressure and at a high temperature. The more truly liquid and volatile portions of the solution pass into the pores of the carbon, and are finally more or less evaporated. This solution is intended to displace the air or other gases which are entangled or occluded in the carbon, and which might otherwise make the rod too soft, or wanting in density. The hole and pores are thus gradually filled with powdered carbon, and ultimately a dense and compact rod is obtained. In the second, or more recent, process, the core is made first and is then placed in a mandril contained in a press, in such a manner that as the mass of carbon paste is pushed along under the action of the plunger, it carries the core, which projects slightly beyond the mandril, with it. The core is usually greyer than the rod itself.

It is customary with direct currents to use a cored carbon for the positive. The core serves the purpose of keeping the crater central, and so conduces considerably to steadiness in burning. In consequence of the relative softness of the core, an arc with a cored carbon for the positive is longer for a given voltage than is the case when the positive is solid. The core is, however, considerably less luminous than the rest of the carbon, due doubtless to the presence of a small quantity of impurity, which,

volatilising at a lower temperature than carbon, is consequently less heated. The intrinsic brilliance of the core has been estimated at 100 candle-power per square millimetre as compared with 158 candle-power for solid carbon. As there is no crater on the negative carbon it should be evident that no advantage would accrue from the use of cored carbons for such purposes, and as a matter of fact they are not so used. When cored carbons are used for alternating current lamps it is necessary that both carbons should be cored, in view of the fact that the two carbons become alternately the positive, and have each of them an immature crater.

The illuminating power of an arc lamp is a somewhat debateable point. The theoretical maximum candle-power which a 10-ampere arc lamp with a cored positive carbon could yield is said to be about 2400, but this assumes that all the light rays emitted by the crater can be made available. Unfortunately this assumption has no basis in fact, owing, in the case of ordinary arc lamps, to the screening effect of the lower or negative carbon. And as a matter of fact the actual maximum with such lamps rarely exceeds about 1400 candle-power, while the average, or, as we shall presently explain, the mean, is much less than that, and is somewhere in the neighbourhood of 850 candle-power. It will thus be seen that the practice which has largely obtained of describing a 10-ampere direct current lamp as being equivalent to 2000 candles is altogether erroneous. As a matter of fact the illumination at an angle of about 50° with the vertical, which is with an ordinary arc lamp in good adjustment the direction of maximum illumination, is only a little over 1400 candle-power.

Mr. A. P. Trotter has demonstrated that, although the end of the positive carbon is hollowed out at the crater, the distribution of the light rays 'is precisely and identically the same as though the end of the positive carbon were flat. No tilting of an incandescent or other luminous surface can make it brighter; and, on the other hand, if it is covered with a thin, imperfectly transparent layer, as in the case of the atmosphere of the sun, the edge will appear less bright than the middle of the disc. The quantity of light emitted by an incandescent disc in any

direction is proportional to the amount of surface visible from that direction.'

The most instructive method of illustrating the manner in which the light from an arc lamp varies at different points in its vicinity is by means of 'polar curves.' It may simplify matters if we first consider the simple state of affairs which would be obtained supposing the source of light (the end of the positive carbon) to consist of a flat disc of uniform luminous intensity, and without the negative carbon near it to cast a shadow. We can then better understand the difference in the distribution caused by the presence of the negative carbon, the precise effect of altering the length of the arc, and the advantages, if any, which result from the fact that the principal source of light at the end of the positive carbon is a crater and not a flat disc.

FIG. 322

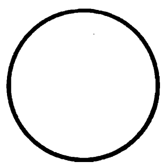
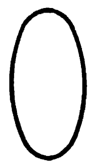


FIG. 323

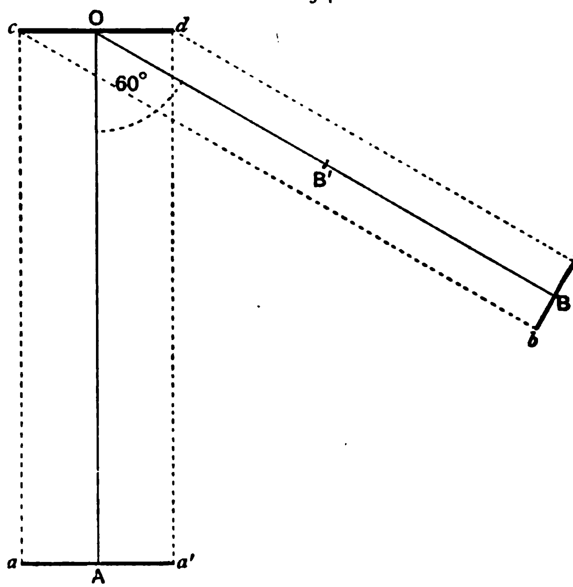


We will assume that this uniformly luminous disc is two centimetres in diameter, as shown in fig. 322. The maximum amount of light would be thrown on a point directly in front of the centre of the disc, and a line drawn from this point to the centre would be at right angles to the plane of the disc, or in other words this line is the *normal* to the luminous surface. The candle-power at any point A along this normal will vary inversely as the square of its distance from the disc. If now a second line be drawn from the centre of the disc, making an angle of 60° with the normal, and a point B be selected, the amount of light here obtained will be less than that at the equidistant point A, simply because, the disc being viewed sideways, a smaller area is effective, although the luminosity per unit of area is the same. The shape of the disc as seen from this point B is given in fig. 323, which should be compared with fig. 322, and if the areas are measured it will

be found that the former is just half that of the latter. Consequently the candle-power at B is half that at A.

A reference to fig. 324 will serve to make this not very difficult matter perfectly clear. The line *c d* represents a side view of the luminous disc; O A is the normal, and O B a line equal in length but making an angle of 60° with the normal, while *a a'* and *b b'* are projections of *c d*, and indicate the extent of *c d* as viewed

FIG. 324



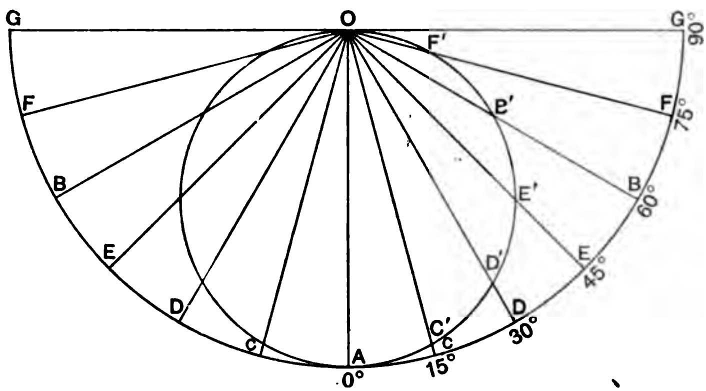
from A and B respectively. It will be found by measurement that *b b'* is half the length of *a a'*.

Proceeding yet further in the same direction, the area visible will fall off as the angle increases, and the amount of light will correspondingly decrease until the angle becomes 90°, when no part of the disc is visible and the light falls to zero.

It requires only a brief inspection of fig. 324 to discover that the length of the projected line (and therefore also the area of the disc visible and the amount of light obtained at any point) varies

as the cosine of the angle made by the normal O A and a line drawn through the given point and the centre of the disc. Knowing this, and being furnished with a table of cosines, we can readily calculate the variation of the amount of light obtained at a number of equidistant points in various positions with respect to O. It is only necessary to multiply the maximum value (obtained along the normal) by the cosines of the angles which lines drawn through the various points make with the normal. For example, we may take seven points A, C, D, E, B, F, G, lines drawn through which make angles of 0°, 15°, 30°, 45°, 60°, 75°, and 90° respectively, and we may represent the light obtained at A by 1000.

FIG. 325



Then the light at A = 1000 × cos 0° = 1000 × 1 = 1000
C = 1000 × cos 15° = 1000 × ·966 = 966
D = 1000 × cos 30° = 1000 × ·866 = 866
E = 1000 × cos 45° = 1000 × ·707 = 707
B = 1000 × cos 60° = 1000 × ·5 = 500
F = 1000 × cos 75° = 1000 × ·259 = 259
G = 1000 × cos 90° = 1000 × 0 = 0

This variation may be even better shown graphically by means of a polar curve, the point O being the pole (see fig. 325).

The larger circle drawn with radius O A passes through points equidistant from O, and the lines O C, O D, &c., make the angles with

the normal as specified above. If now on each of these lines we set off a length from O, proportional to the cosine of the angle which the particular line makes with the normal, we obtain a length which indicates the amount of light obtained at the point under consideration. For example, since the cosine of 60° is 0·5, the length O B′ is half that of O A, while O F′ is 0·259 of O A, and the lengths O B′, O F′ indicate the amounts of light obtained at B and F respectively. On taking a large number of values and joining the points so determined, we obtain a circle passing through the pole O, its centre being the middle point of O A.

This circle does not fully represent the distribution of the light, but a sphere having the same radius would do so. The sphere, in fact, is the one which would be described if the circle were made to revolve about its vertical axis O A, and the radius of this sphere is a measure of the spherical candle-power.

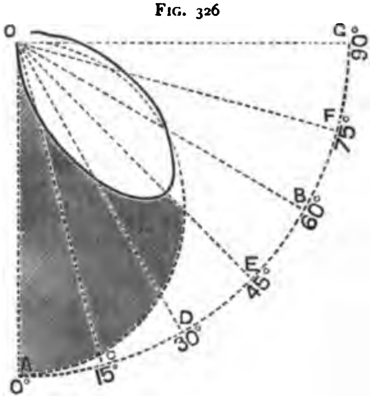
The same units of length always being employed, it is evident that the spherical candle-power would be a convenient method of effecting comparisons. In the case of an actual arc, several causes combine to prevent the distribution of light being so regular, but a curve may be plotted, and the solid content of the space enclosed by this curve when it revolves about the vertical axis can then be calculated, and the radius of the sphere whose solid content is equal to that thus obtained gives a value by which comparisons may be effected, known as the mean spherical candle-power.

We shall presently give an instance illustrating this method, but may now consider the simple reasons, first clearly pointed out by Mr. Trotter, which give to the candle-power curve for an actual arc lamp its peculiar shape. In the first place, while the end of the positive carbon is without doubt the original source of practically all the light obtainable, the negative carbon is necessarily placed directly opposite it, in the path of the greatest illumination O A, and it intercepts a very large proportion of the light, casting a shadow on what would otherwise be the most brilliantly lighted area. In this position also sufficient energy is expended upon the negative carbon to make it appreciably luminous, and it throws its light upwards, illuminating slightly the space above the horizontal line G O G. (fig. 325). Further, the end

of the positive carbon itself is not a simple luminous disc, but a hollow crater, varying slightly in depth and position, and even giving some light from the outside edges of its walls, and this latter fact tends to increase the light emitted in a horizontal direction.

Fig. 326 shows the candle-power curve obtained from an ordinary arc lamp in good adjustment. The shaded area represents the screening effect of the lower carbon, and it will be seen that in this particular instance the maximum illumination is obtained along a line making an angle of 45° with the normal. By lengthening the arc so as to reduce the screening effect, the line of maximum illumination would be brought lower down or nearer to the normal, and *vice versa*. The increase in the horizontal illumination as well as the slight illumination above the horizontal line should be noted. This curve represents, as has already been indicated, the illumination at the equidistant points G, F, B, &c., in a vertical plane on one side only of the arc, and if the curve were rotated round O A the solid figure thus swept out could be expressed in terms of the equivalent sphere as the most convenient way of effecting comparisons.

FIG. 326

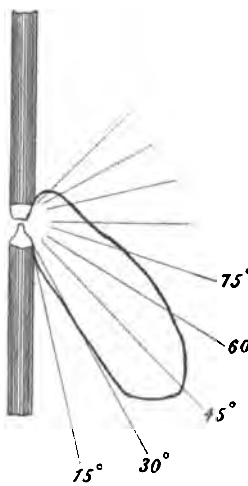


As shown by Mr. Trotter, an almost identical curve can be obtained by plotting the values, not of candle-power, but of the areas of the crater visible from the respective points, and this result should follow from the fact already mentioned that the intensity of illumination per unit area of the crater is uniform and a constant quantity for the same kind of material in any kind of arc lamp. We may here mention a method of determining approximately the mean spherical candle-power of an arc lamp by means of two photometric measurements only, one in the same

X X

horizontal plane as the arc, and the other in the direction of maximum illumination. One-fourth of the maximum candle-power added to one-half of the horizontal candle-power gives the mean spherical candle-power. The curve which is yielded by an arc imperfectly adjusted or between inferior carbons departs considerably from that illustrated in fig. 326, and a curve obtained from a lamp burning under such conditions is illustrated in fig. 327. The irregularity of the curve is very noticeable. The arc was apparently a short one, and the negative carbon was, therefore, unduly heated, thereby giving rise to the 'hump' on the curve above the horizontal. The current would also appear to have been excessive and the arc on the point of hissing.

FIG. 327



Objection has been raised to the estimation of the efficiency of an arc lamp on the basis of its mean spherical candle-power, inasmuch as two lamps might have the same value on this basis and yet behave very differently as illuminants. As a case in point it will be seen that if the direction of the current through a lamp were reversed, so as to make the lower carbon positive, the curve in fig. 326 would be inverted, and, although the candle-power would be unaltered, very few of the rays would fall below the horizontal, and the illumination would be correspondingly weakened. While, however, this contention is in a large measure justified, it should be evident that, if correct polar curves are obtained, the direction of maximum illumination is readily seen, and the useful lighting powers of different lamps can easily be compared.

For a variety of purposes arc lamps which direct their rays upwards instead of downwards are very useful. Such lamps are known as inverted arc lamps, and are extensively used for drawing-office purposes. The lower carbon is made the positive, and the design of the lamp is correspondingly modified, a large

reflector being placed under the lamp so as to project upwards the rays from the negative carbon and any others that may happen to fall below the horizontal plane. Obviously to get the best results the ceiling and upper portions of the walls should be white and kept scrupulously clean so that the maximum reflection may be obtained. A table showing the reflecting powers of surfaces of various materials and colours will be found in Chapter XVI.

So far our remarks have applied almost exclusively to direct-current arcs, but it has been pointed out that alternating-current arcs have the disadvantage that no true crater is formed in either carbon, and that the luminosity is in consequence much smaller in amount, and, as we shall see presently, the efficiency is lower. Alternating current arcs have, however, one advantage, and that is that the majority of the luminous rays are projected horizontally, and have therefore more frequently been adopted for lighthouse purposes.

Alternating-current lamps are usually attended by one serious objection, viz. a remarkable humming sound which is pitched in unison with the rate of reversal in the alternator itself. Among the chief causes of this phenomenon is the vibration of the laminated magnet cores and other parts of the lamp not rigidly fixed. Another cause is the oscillation set up among the iron particles by the rapid reversal of the magnetisation ; this is to some extent overcome, or at least lessened, by shortening the cores of the electro-magnets as much as possible. The lamination of the cores also tends to reduce the loss of energy due to the generation of eddy currents. Another suggested cause for the humming is the 'rapid periodic extinction and re-establishment of the discharge' between the two carbons. This type of lamp is less efficient than one supplied with a direct current. As has been already pointed out, the alternations prevent the development of a true crater, and consequently there is proportionally less volatilisation. The virtual E.M.F. necessary for an ordinary alternating arc is not more than 38 volts, but the actual range is from zero to a maximum of about 50 volts, and there is reason to suppose that it is only during the momentary duration of these higher voltages that there is any effort to raise the carbon to its standard temperature of volatilisation. The light which is obtained is mainly due,

therefore, to the more or less incandescent ends of the carbon rods, both of which are tapered. It must also be noticed that while a large proportion of the rays are directed horizontally, the number of rays projected upwards, and therefore, generally speaking, wasted is equal to the number directed downwards; on the other hand, the distance between the carbons is, in lamps of normal size, greater than with a direct-current lamp, so that the screening of one carbon by the other is lessened; it is also lessened in consequence of the more perfect taper of the carbon ends.

The power taken by an ordinary alternating arc with a current of 10 amperes under a pressure of 38 volts is but 380 watts, as compared with 500 watts for the direct-current 10-ampere lamp, the luminosity being of course considerably lower. It is a disadvantage that the arc can be maintained at this low pressure: indeed, a lamp which would require 100 volts in order to yield its maximum intrinsic brilliance would be more advantageous, because the efficiency would be greater and the current which would be taken would be proportionally reduced, the losses in resistances and choking coils in parallel working (to which a future reference will be made presently) being proportionally lessened. During those portions of the cycle of voltage when the pressure is low—lower, in fact, than that required for volatilisation—such light as is developed is due to carbons which are really undergoing a cooling process. In fact, when the illumination obtained is compared with the power expended, the alternate current is, as we have said, less efficient than the direct current, and this to some extent accounts for the comparative discredit into which alternate-current arc lighting has fallen.

The resistance of the coils and the carbons in an arc lamp causes, naturally, a certain fall of potential consequent on the passage of the current through them. This fall is usually about 5 volts. Hence, although a good direct-current 10-ampere arc can be maintained with a pressure across the arc itself of 44 or 45 volts, as much as 50 volts must be applied to the lamp terminals. Assuming the current to be 10 amperes, it follows that the power absorbed in the lamp is 500 watts, and, the mean spherical candle-power being about 850, it follows also that we have 1·7 candle per watt. This ratio we may call the efficiency

of the lamp. It should be evident that if a 500-watt lamp gives a mean candle-power of 850, a lamp which would consume one electrical horse-power, or 746 watts, should yield a light of about 1268 candle-power. Allowing, however, for the various losses in a lighting system, such as those due to the resistance of the conductors and of unsoldered connections, and the losses due to conversion in the dynamo, the engine will indicate one horse-power for each 10-ampere or 850-m.s.c.p. (mean spherical candle-power) arc lamp.

The diameter of the carbon rod varies with the light it is required to give or the current it is required to carry, those most frequently in use for 10-ampere lamps being 11 and 9 millimetres in thickness. The lower or negative carbon is, in direct-current lamps, usually thinner than the upper one, the object being to reduce the loss of light due to the screening of the crater and to take advantage of the slower consumption of the negative rod. Mr. Trotter, in discussing this question, observes in his characteristic style that 'the diameter of the positive carbon is easily settled; if it is too small the arc will hiss, if it is too large the crater will wander. The negative carbon must carry the current satisfactorily, and should be as small as will stand handling.' Returning to the question of efficiency, it may be noted that an ordinary 13-millimetre carbon offers a resistance of about 0·175 ohm per foot, whence with a 10-ampere current the fall of potential in that length of carbon is 1·75 volt. If now we suppose one foot of carbon to have been consumed and the pressure of 50 volts to be still maintained, then the energy previously expended upon the carbon is available for the other portions of the lamp circuit. The resistance is, in fact, materially reduced, and the result is that there is a proportional increase either in the strength of the current or in the length of the arc.

Again, it should be remembered that there is frequently a slight variation in the condition and resistance of the arc itself, but it is very desirable that the current in practical working should be kept as uniform as possible. We cannot entirely avoid variations of resistance; so, in order to make those variations of minimum effect, it is the practice, when lamps are connected in parallel across a pair of mains at a constant potential difference,

to work with a higher pressure than 50 volts, and to insert, in series with the individual lamps, resistance coils capable of absorbing the excessive volts, or of keeping the potential difference between the ends of the rods fairly uniform. For example, it is frequently the practice to place the lamps across a pair of conductors having a potential difference of 65 volts, or 15 volts more than is necessary for supporting the arc. This means that a coil of wire, say of iron, has to be used; it must be large enough to carry a current of 10 amperes, and, letting e represent the extra volts, the wire must offer a resistance of $r = \frac{e}{\text{C}} = \frac{15}{10} = 1\cdot5$ ohm. The function of the added resistance is, as we have indicated, to make the total resistance of the particular lamp circuit such that small variations of resistance in the lamp shall, by being spread over a greater resistance than that of the lamp itself, make the proportional variation more or less negligible, and thereby maintain an almost uniform current through the lamp, and this will involve the maintenance of a practically uniform potential difference between the carbons. As a consequence, the arc is steadied, and an equable illumination results. This method is somewhat costly, for instead of taking $\text{E} \times \text{C} = 50 \times 10 = 500$ watts, the absorption of power is increased to $(50 + 15) \times 10 = 650$ watts, or an increase of about 30 per cent., while the efficiency is reduced to $1\cdot3$ candle-power per watt. It is preferable to employ a pair of mains with a potential difference of, say, 110 volts, and join two arc lamps in series between them. The lamps taking 100 volts, there remain only 10 volts to be absorbed by the steadying resistances for the two lamps; and the length of the coil of wire is also reduced, for, having now to absorb only 10 volts, its resistance is only $r = \frac{e}{\text{C}} = \frac{10}{10} = 1$ ohm. This will absorb $e \times \text{C} = 10 \times 10 = 100$ watts, and the lamps together with the resistance will absorb $110 \times 10 = 1100$ watts, or an increase of 10 per cent. upon the power actually absorbed in the two lamps. The gain is obvious. With really first-class lamps it is, however, possible to join two lamps in series on a 100-volt circuit without any steadying resistance at all. In that case the resistance of one lamp is relied upon to reduce the otherwise baneful effects of a variation in the resistance of the other lamp.

When a larger number of lamps are joined in series there is manifestly no necessity for any added resistance; and this is one of the advantages of the general increase in the voltage supplied by the majority of central stations, although, unfortunately for the purposes of arc-lamp users, the voltage is not usually a simple multiple of 50. For example, the voltage provided is often 220 or 230 volts, and in such cases 20 or 30 volts have to be wasted, or the resistance of the series circuit through the lamp be made so low that five lamps can be joined in series. There is, of course, the alternative that four lamps may be joined in series and a longer arc be allowed, so as to take up the total volts, but the experiments which Mrs. Ayrton has made render it doubtful whether this practice is economical from an illuminating point of view. Her experiments, in fact, appear to indicate that when the arc is lengthened and a correspondingly higher voltage is provided, the additional rays which would otherwise be available are absorbed by internal reflections and refractions in the arc and in the vapour or mist which envelops it. When the voltage supplied is 240, five good lamps can be joined in series with impunity, for then there are 48 volts available for each lamp, and this is, in the circumstances, sufficient.

When alternating-current lamps are run in parallel, a 'choking coil' takes the place of the comparatively high resistance coil employed with the direct current. The choking coil was referred to in Chapter XIII., and it will be remembered that it consists of a substantial iron core with a comparatively few turns of thick copper wire round it, and it may in addition be completely encased in iron. The combination offers an inappreciable resistance, but it has considerable self-induction, which sets up a counter or back E.M.F., and so enables a fall of pressure to be obtained with a comparatively small absorption of power. Consequently, any variation in the pressure between the carbon points becomes a smaller proportion of the total pressure, and has therefore less effect than would be the case in the absence of the choking coil. Such coils are also occasionally used, in place of ordinary resistance coils, on a direct-current parallel circuit with the object of reducing the sudden rush of current through the lamp before the arc is struck, and also in order to minimise any sudden variations in the current strength while running. In

such a case the resistance of the choking coil must be equal to that of an ordinary coil if used for the same purpose.

The use of globes considerably reduces the amount of light actually obtained from a lamp. The proportion of light cut off by globes has been determined to be:

For clear glass . . .	about 10 per cent.
„ light ground glass . .	„ 30 „
„ heavy „ „ . .	45 to 50 „
„ strong opal „ . .	50 to 60 „

These figures refer only to clean globes, but an additional 30 per cent. of the remaining effective rays may easily be lost when the globes are allowed to become dirty. The figures will no doubt strike the student as being very high, perhaps unduly so, but if he is in the least degree observant he cannot fail to notice the enormous difference in the illumination of the ground when a piece of any ordinary arc lamp globe has been broken away, more particularly when the fracture is somewhere near the angle of maximum illumination.

Apart from the cost of the power required by an arc lamp there are also to be considered the cost of the carbon rods and of the necessary labour involved in 'trimming.' A good steady arc maintained between 13-millimetre carbons with a current strength of 10 amperes will consume 1·0 to 1·5 inch per hour. For example, we may mention that in one set of tests with six 10-ampere lamps, using 13-millimetre carbons, the positive being cored and the negative solid, we obtained the following as the result of 11 hours' running:

Lamp	Carbon consumed in 11 hours		Consumption per hour		
	Positive	Negative	Positive	Negative	Total
	inches	inches	inch	inch	inch
A	11·125	5·500	1·011	0·500	1·511
B	10·812	5·500	0·983	0·500	1·483
C	10·250	5·500	0·932	0·500	1·432
D	10·125	5·125	0·920	0·466	1·386
E	10·615	5·100	0·965	0·461	1·426
F	10·250	5·000	0·932	0·454	1·386

It is hardly within our province to enter here into the cost of the various items and materials used in electric lighting, but it will be evident that there is in every lamp a certain amount of waste. Enough carbon must in the first place be inserted in the holder to insure sufficient contact; this is waste. The carbon cannot be burned nearer than within, say, half an inch of the holder; this also represents waste. It is, moreover, all but impossible to gauge the actual time during which a lamp is required to burn on any particular occasion. Hence if, in trimming, the carbon is found to be within an inch or two of the holder, it must be removed and a new carbon substituted; this is more waste. Altogether on an installation comprising a number of arc lamps the carbon wasted may easily amount to some thousands of feet in the course of a year. One way of reducing this loss is to employ double carbon lamps, or lamps which carry two pairs of carbons. One pair, as will be shown in describing the Crompton lamp, is (automatically) lighted first, and, after having burned down to within a small but certain predetermined distance from the holders, the current is automatically diverted and made to pass through the other pair. This reduces the waste to a minimum, but it means that extra complications must be introduced into the lamp, sometimes at the cost of reliability, and it is a device which is not resorted to unless really necessary.

Coming now to the question of the construction of arc lamps, it should be observed that if the source of light is, for focussing purposes, required to remain stationary—which is, for lighthouse or lantern work, of paramount importance—both carbons must be automatically movable at their respective rates of consumption; but when this is not absolutely necessary, as, for example, in ordinary street or shop lighting, then it is only necessary that one carbon should be fed forward towards the other, which can then be supported in a fixed socket, and gradually burned down. The latter form of lamp is, in the case of direct-current working, somewhat simpler in construction and correspondingly cheaper than the former, or 'focussing,' type.

Arc lamps may be used either in series on a circuit through which a *constant current* is sent, or in parallel, when they would have a *constant potential difference* maintained at their

terminals, but the difference between the requirements is small. Lamps intended for series working were at one time provided with an automatic 'cut-out,' an adjunct which, when the main circuit through the lamp was from any cause interrupted, introduced an alternative path of low resistance, so that the other lamps on the circuit remained unaffected. Break-downs of this character are now, however, somewhat rare, and the cut-out is, except on long circuits, frequently dispensed with. Where it is necessary to employ a cut-out, the apparatus is generally made separate from the lamp, and is frequently fixed in the plinth of the lamp-post.

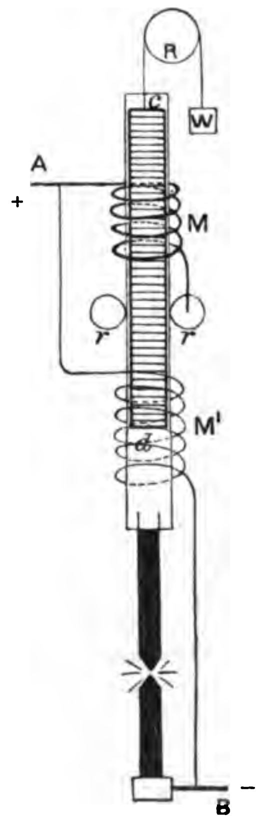
A lamp which is intended for simple parallel working might be easily made. In fact, if we suppose the lower carbon to be fixed, and the upper one carried in a sliding holder which either takes the form of or is continuous with an iron rod of suitable dimensions, then the only other essential is a thick-wire coil which shall on the passage of the current be competent to raise the upper carbon just far enough to strike the arc. The attractive power of this coil should be so adjusted that when the arc elongates sufficiently to cause an undue increase in its resistance, and therefore a proportional decrease in the current strength, it should be incompetent to sustain the weight of the core and carbon. These would then fall sufficiently near to the lower carbon to restore the current to its normal strength. This would, however, be a rather crude type of lamp, and a somewhat more elaborate design is therefore adopted.

In all cases, however, it is essential that the lamp should automatically 'strike' its own arc, and this action must perforce be controlled by the current—that is to say, the separation of the carbons must always be brought about electrically. In most cases the coil for this purpose is placed in the main circuit, and is usually referred to either as the main or the series coil.

It rarely happens in modern practice that arc lamps are worked on the simple parallel system. The usual practice is to join them in sets of two, four, or more lamps in series across mains which are supplied with a corresponding potential difference. Under another system, known as the series system, which was at one time very prevalent in this country, and which still

obtains to some extent elsewhere, as many as 40 or even more lamps are joined in series, and the current is kept constant independently of the number of lamps in circuit; that is to say, when the number of lamps is varied, the potential difference applied to the series is varied proportionally, so that a constant current through each lamp is maintained independently of any variation in the resistance of the arc. In all these cases it is necessary to provide a second coil, which, by acting in opposition to the striking or series coil, feeds the carbons forward when the length of the arc becomes too great. The second solenoid is joined across the lamp terminals, forming a shunt to the series coil and the arc, and is known as the 'shunt' coil. In some cases the carbons only are shunted, the whole of the current passing through the series coil; but the object is always the same, viz. to keep the potential difference between the carbons constant. The striking or series coil is of low resistance, while the feeding or shunt coil is of high resistance. As these coils have antagonistic effects, the lamp is called 'differential.' This is the principle upon which the majority of arc lamps are constructed, whether for parallel or series working. Some of these so-called electrically controlled lamps, however, involve delicate mechanical contrivances. To be purely electrical, the moving carbons would require to be perfectly balanced, and only movable under the preponderance of the effect of one coil over that of the other.

FIG. 328



The fundamental principles involved in an electrically controlled differential arc lamp are illustrated in fig. 328. The

current on arriving at A is divided between the two paths, one of low resistance and the other of comparatively high resistance. The former (the main or striking circuit) includes the thick wire coil M, from which the current passes to the contact roller *r*, and thence through the frame to the upper or positive carbon holder, the circuit to B being completed through the arc and lower carbon holder. The other, the shunt or feeding circuit, consists of the coil M¹, which comprises many turns of fine wire, its ends being connected to A and B respectively. These coils are, in the design illustrated, wound upon a brass tube, inside which another brass tube is loosely fitted, so that it can slide up and down freely. An iron core, *c d*, is fixed inside the inner tube, and is almost balanced by a weight W attached to a cord passing over the pulley wheel R.

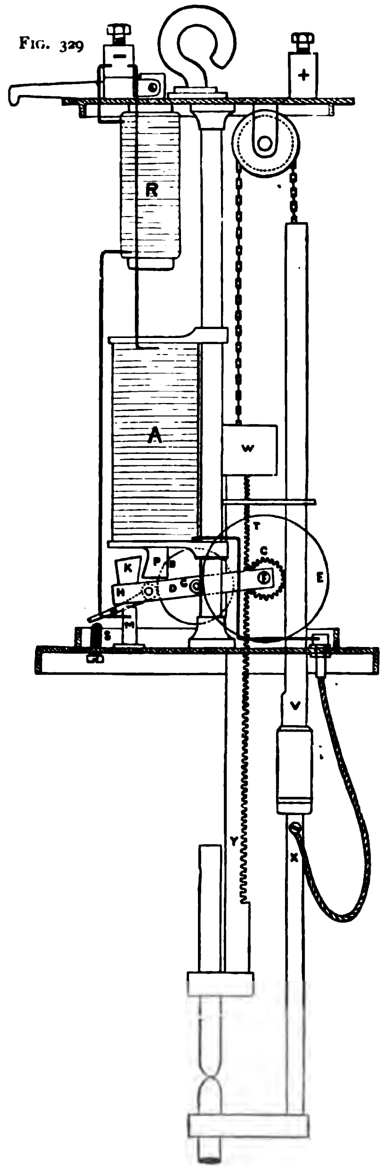
When the current is switched on, nearly the whole of it passes through the striking coil M and the carbons, which are at that moment touching one another. The coil consequently exerts a strong attraction upon the core, and raises it sufficiently to separate the carbons and strike or start the arc.

The resistances and the number of convolutions of the coils M and M¹ are so adjusted that, the arc having been struck and having arrived at the proper length, their action upon the core is exactly balanced. Any increase in the resistance of the main or series circuit, caused by the consumption of the carbons and a corresponding increase in the length of the arc, disturbs this balance, increasing the current through the shunt coil, and reducing that through the series coil, whence the core, with the upper carbon attached, is attracted downwards by the shunt coil, and in descending again restores the balance, readjusting the arc to its normal length. In the event of a disconnection between the carbons such as might happen before lighting up, the coil M¹ takes the whole of the current flowing through the lamp and continues to draw the core down until the two carbons enter into contact. Immediately this happens a heavy current passes through M at the expense of M¹, and the core and upper rod are raised sufficiently to establish the arc. The arrangement is very sensitive, and the two coils are designed so to react one upon the other that there is no apparent fluctuation in the light, and the two carbons are kept uniformly apart from the first striking

of the arc until the current is switched off or the carbons are consumed.

A typical form of electro-mechanical differential arc lamp is illustrated in fig. 329. This type of lamp, although its mechanical design is good, is expensive to make. Few modern makers can go to the expense of providing a rack-rod, which to be effective must be of really first-class workmanship to ensure steady running. An electro-magnet A is wound with both the series and shunt coils, but normally the current travels through the two coils in opposite directions round the core, which terminates in the pole-piece P. This pole-piece acts upon an armature, K, fastened upon a frame, H D, pivoted at F. This frame also carries a brake wheel B, on the axle of which is fastened a small pinion G, and brake lever N made to grip B by a helical spring wound round the axis, by which it is attached to the frame H D. The pinion G gears into the larger toothed wheel E, on the axis of which is another pinion, C, engaging with the rack-rod Y, to which the positive carbon rod is attached. This rack-rod is

FIG. 329



connected at its upper end to a weight W, which is carried by a chain; this arrangement allows the positive rod in descending to lift the negative rod V X. When no current is flowing, the brake lever N rests on the screw S, which releases the brake wheel and allows the carbons to come into contact. The current enters at the positive terminal on the right hand of the figure, passes through the framework of the lamp to the rod Y, and thence to the positive carbon. It returns from the negative carbon by the insulated rod X and the flexible conductor attached to it, passing through the thick wire or series coil on A, and from this to the negative terminal. The magnet attracts K, raising the frame H D, thus causing the lever N to grip the brake wheel, and, by turning E and C, to raise Y and lower X for the purpose of separating the carbons and striking the arc. As the carbons burn away and the arc lengthens, its resistance rises, whence the current through the series coil diminishes, while that through the fine wire or shunt coil round A, which is connected as a shunt to the lamp terminals, increases. This weakens the magnetisation of the core of the electro-magnet, and therefore also the magnetisation of the pole-piece P, and allows the frame H D to fall until, when the lever N comes in contact with the screw S, the brake is released, and the carbons are allowed to approach. By this means the balance of current in the series and shunt coils is re-established and the arc maintained in a normal condition. If the carbons burn out, or if from any other cause the circuit through them is broken, the frame H D drops on the contact pillar M; this completes the circuit from the lamp frame through the German-silver resistance R to the negative terminal, thus forming a 'cut-out' or alternative path, which has the effect of preventing, in the case of a circuit with a number of lamps in series, a break in the continuity of the circuit—that is to say, the other lamps in series with it will continue to burn uninterruptedly.

It will, of course, be understood that the current which passes through the shunt represents so much waste or lost energy, but it will have been noticed that the shunt coil is of thin wire and therefore offers a relatively high resistance, so much so that in ordinary circumstances the current passing through it is only about 1 per cent. of the total current passing through the lamp,

and the loss is in such cases limited to 1 per cent. The student will also notice in connection with some of the lamps described later that a 'dashpot' is provided, in order that the movements of the carbons shall be gradual and not jerky, and thereby to minimise the effect upon the arc which would otherwise result from the alterations in the length of the arc.

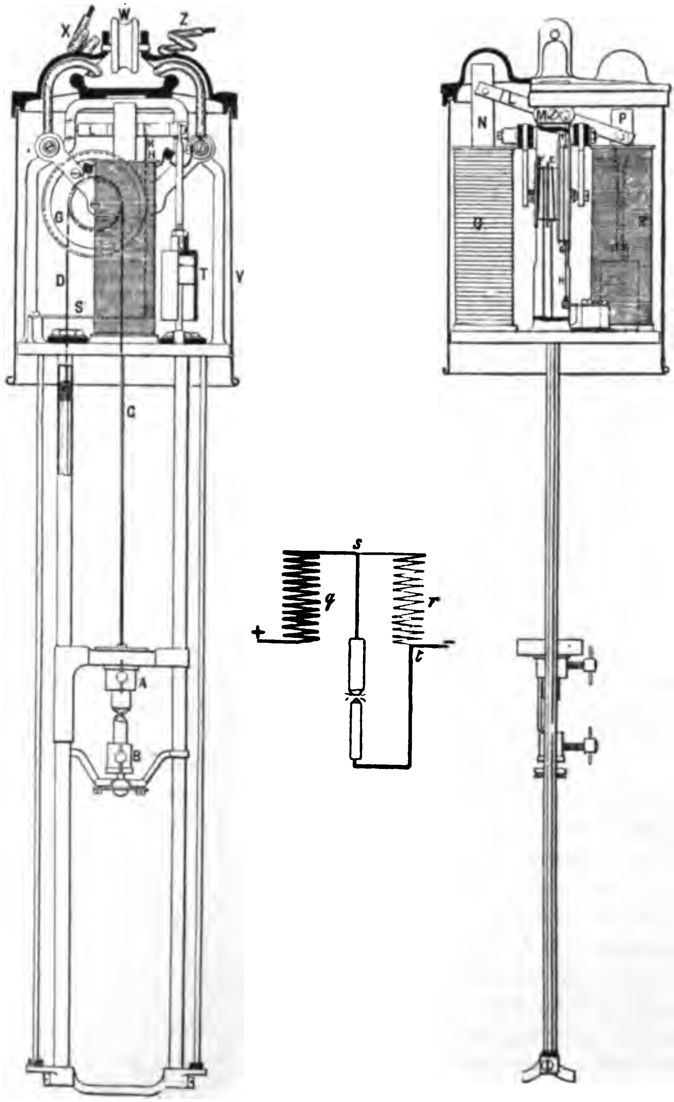
FIG. 330

The Brockie-Pell arc lamp is illustrated in fig. 330. It is a lamp which was for a long time regarded as one of the very best obtainable, and this was the result of careful design and more particularly of good workmanship. Other lamps have outstripped it, but we have many of them which were installed some fifteen years since still in use, and which are working almost as well to-day as they did when the current was first switched through them. The main and shunt coils are wound on separate bobbins fixed parallel to one another. The two cores are attached to the ends of and operate a 'see-saw' lever which is pivoted at its centre. The two carbon holders are connected by a cord passing over a pulley wheel pivoted on the base of the lamp-case. The upper or positive holder is provided with a rack-rod which gears into a pinion; the spindle of this pinion works in the frame of the lamp, and carries a comparatively large wheel having a strong broad rim, against which a brake in the form of a small leather roller is applied. The lever carrying this brake turns on a weighted sector-shaped lever, which is loosely pivoted but moves solidly with the brake wheel, its descent being, however, limited by a stop; the outer end of the brake lever is connected with the link supported by the see-saw lever.

On the passage of the current the striking coil raises its end of the lever, applies the brake to the wheel, and raises the positive carbon, the negative carbon being caused to recede at the same time. The arc is therefore established. As the arc lengthens and the main current diminishes, the shunt current increases and the other end of the see-saw lever is elevated; consequently the brake lever is depressed, the brake wheel released, and the carbons are allowed to 'feed' together. These reactions take place readily, the feed being practically continuous, and a steady light can be maintained even with a variation in the main current of 20 per cent. above or below the normal working current. The initial adjustment for balancing the carbon holders to operate with any particular strength is effected by means of weights.

Coming now to the question of present-day types of lamp, the number of classes, if we attempt fully to classify them, is almost as great as the number of manufacturers. It will therefore suffice if we say that most of them are differentially wound, that they are designed to be run with two or more in series, and that very few indeed depend entirely upon electrical control. The description of one of these modern lamps will therefore meet the requirements of the student, and we have selected for the purpose the Crompton lamp, the construction of which is illustrated in fig. 331. The figure gives two views of the lamp. The carbon holders A B are attached to independent flexible metal cords C D, which are wound in opposite directions on two metallic drums, E F, insulated from each other by a mica disc, but arranged to rotate on the same axis. The cords C D, in addition to supporting the carbon holders, serve the function of transmitting the current to the carbons. A third drum, G, of larger diameter than E F, is mounted on the same axis, and the striking of the arc and the feeding of the carbons are actuated by a band brake, H, passing over this drum. The upper end of the brake cord H is attached at K to a rocking lever L, which is pivoted at M. Hanging from the ends of the lever are two mild steel cores, one of them, N, extending into the thick wire solenoid Q, which constitutes the main or series coil; while the other core, P, extends into the thin wire high-resistance solenoid R, which is joined in parallel with the arc, and which we have referred to as the shunt coil. The arrangement is

FIG. 331



such that when the series coil attracts its core, N, downwards, the lever lifts the brake cord H, the lower end of which is attached to a flat spring S.

Prior to the switching on of the current the carbons are in contact, being drawn together by the greater weight of the upper or positive carbon holder as compared with the lower. The electrical circuit through the lamp is further illustrated by the small diagram, where *q* and *r* represent the series and shunt coils respectively. It will be seen that the whole of the incoming current passes through the series coil and that the shunt coil is a shunt across the arc only. The carbons being in contact, it follows that when the current is switched on, the resistance of the circuit through the carbons is very low and the current is in consequence above the normal. As, however, the resistance of the arc circuit, that is to say, between *s* and *t*, is very low, the potential difference between those points is also very low; whence the current through the shunt coil is small. As a consequence the core N is drawn down by the series coil, and the upper end of the brake cord is raised. As soon as it has been raised sufficiently to tighten it, the cord grips the brake drum G, and, continuing to rise, turns the brake drum with it and bends the spring S. The brake drum, in turning, strikes the arc and draws the carbons apart until the arc is of the correct length. The lamp is so adjusted that when it reaches this position the pull on the ends of the lever L, due to the attraction of the cores N P, the weights of the various parts, and the tension of the spring S are all in balance. As the carbons burn away, the resistance of the arc increases, and the potential difference between *s* and *t* rises, whence the current through the shunt coil becomes stronger and tends to pull down the core P. In order, therefore, to re-establish a balance, the lever L has to take up a position with the carbon holders slightly nearer together; and these reactions continue, the balancing of the lever counteracting the effect of the burning away of the carbons until the lever is in such a position that the spring S is almost in its released position. When in this position, the tension on the brake cord H being reduced, the brake drum, under the action of the heavier positive holder, is allowed to slip slightly, and thus the carbons feed together.

When the current is switched off, the lever falls over so that the shunt core is down and the series core up, and the carbons are allowed to run together. The lamp is then in a position for re-lighting.

As we have already indicated, it is necessary to provide against any violent action, such as might arise, for instance, from a broken carbon, and this provision usually takes the form of a dashpot, which generally consists of a cylinder and piston. The dashpot in the lamp in question is at T. It is fitted with a special graphite plunger, fitted at its upper end to the lever, and effectively acts as a damper and prevents any sudden violent action. The whole frame of the lamp is insulated from the 'live' or current-carrying parts, and is not utilised in any way in the electrical circuit through the lamp. The frame itself is also insulated from earth by a porcelain suspension insulator W, so that the lamp is capable of standing a high insulation test.

The mechanism is protected by a cover V, and is so arranged that the lower rods and parts exposed to fumes and carbon dust can be cleaned when the lamp is being trimmed without exposing the mechanism.

The leads X Z are led in through specially shaped holes in the cover, so as to keep the lamp waterproof. Of course the lamp can be fitted so that it can be screwed on to a pipe or bracket, and attachments which are not shown in the figure are provided for supporting a globe or lantern. The lamp is well suited for inversion, and we have used a number of the inverted lamps in drawing-offices with good results.

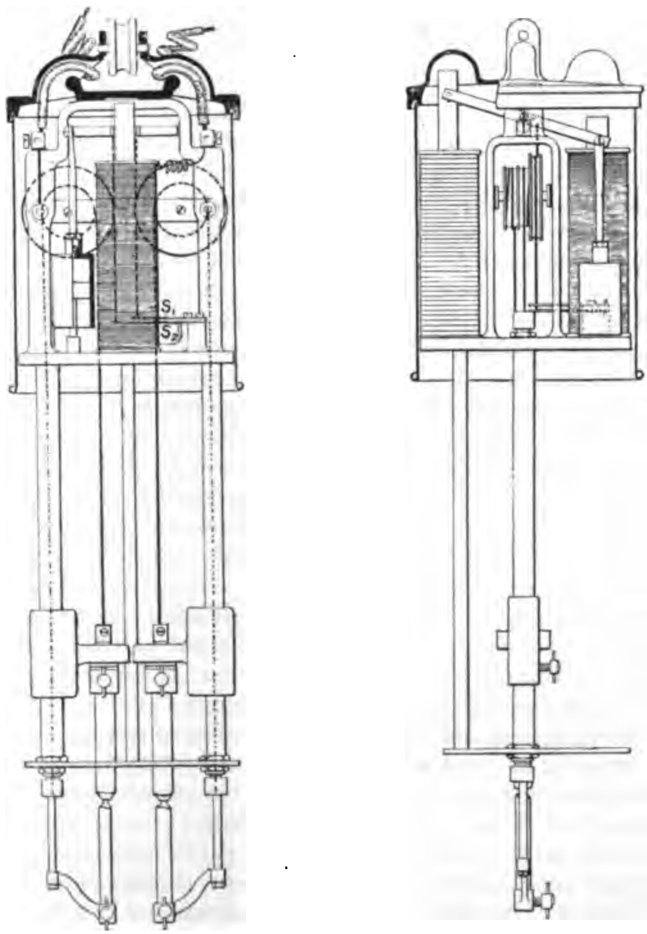
The lamp is made in two standard sizes, designed for burning 10 and 16 hours respectively. For some purposes, such as street lighting, longer burning hours are required. This is accomplished by the provision of a double carbon lamp. We have already referred to the loss due to waste carbon ends, and it will be seen that if a lamp has to burn for, say, 12 hours every night, and if it is impracticable to stop it during its run for trimming purposes —if also the life of the carbons be 16 hours—one-fourth of the carbons will have to be thrown away when trimming for the next night's run. In the double-carbon lamp there are, as the name implies, two sets of carbons, their united life being therefore

32 hours. One pair of carbons is burnt for the first night's run and for the first four hours of the second, when that pair will have been consumed, and the current is then automatically diverted to the second pair for the remaining eight hours. At the end of the second night one half of the second pair of carbons will be left, and instead of throwing these eight-hour lengths away they can be left in the lamp and the burnt-out carbons replaced without waste. The lamp would then be trimmed for a run of 24 hours, or two nights, when the carbons would be consumed completely. There are thus two advantages pertaining to double-carbon lamps, viz. availability for extra long runs and reduced wastage of carbon. On the other hand, it is obvious that as there must be more working parts in a double than in a single carbon lamp, the latter is the simpler and correspondingly less likely to be deranged.

The Crompton double-carbon lamp is illustrated in fig. 332, and it will be seen that the general design is the same as that of the single-carbon lamp, with the main exception that there are two sets of drums, each controlling its own pair of carbons, each pair being acted upon by a separate brake cord, and each brake cord attached to a separate spring. The upper ends of the two brake cords are, however, attached to the same lever, which is actuated by a series and a shunt coil as before. The point which requires attention is the means provided for allowing one pair of carbons to feed before the other. This is arranged by so adjusting the lengths of the brake cords that one spring, say s_1, is tightened before the other, say s_2. If the spring s_1 attached to the cord controlling the right-hand pair of carbons (as shown in fig. 332) tightens first, those carbons are pulled apart, while the other pair of carbons is still in contact. No arc is therefore struck between the right-hand pair, but the movement of the lever is continued until the left-hand pair is separated, and an arc is then struck between the latter pair. When, as the left-hand pair is consumed, the carbons begin to feed together, the lever never comes down far enough to release the spring s_1, and the right-hand pair is therefore kept apart until the left-hand pair has been consumed. As soon, however, as the left-hand pair has been burnt out, so that the holders are unable to move any

further, the arc lengthens, until eventually the lever takes up such a position that the spring S_1 is released. The change-over then

FIG. 332

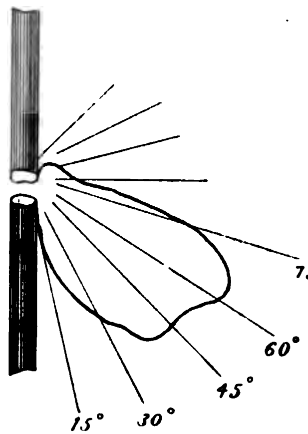


takes place, the right-hand pair of carbons is allowed to make contact, and then to strike the arc.

So far we have been dealing with lamps in which the carbons are surrounded by a practically continuous supply of fresh air, and in which every possibility is afforded for the consumption of the carbons by ordinary combustion—that is to say, by the chemical combination of red-hot carbon with atmospheric oxygen. It will be remembered that this results in the tapering of both the positive and the negative carbons. We come now to the consideration of a very different type of lamp, from which air is almost entirely excluded, and which is known as the enclosed arc lamp. One of the earliest and most persistent workers in the development of this type of lamp was Mr. Marks, and his experiments have opened the way for many others. The fundamental principle of the enclosed arc lamp is that the two carbons are confined in a small and almost hermetically sealed opalescent glass globe or cylinder, and that after a very short time the contained oxygen will have been combined with the carbon, and the arc is thenceforward maintained in an atmosphere of carbon oxide gas and the inert gas nitrogen, so that no further 'combustion' of the carbon rods is possible. At the same time the heat due to the arc considerably increases the pressure of the gases contained in the small globe or cylinder, and as the means of egress is very limited, the pressure upon the arc itself increases. The effect is to cause an increase in the voltage necessary to maintain a given current, due probably to an increase in the temperature at which the carbon can volatilise, in the same way that an increase in the pressure on water raises its boiling-point. Further, owing to the continued presence of an atmosphere devoid of oxygen but rich in carbon vapour, the length of the arc can be increased, and a correspondingly higher voltage applied. As a consequence enclosed arc lamps can be joined in parallel across mains at a potential difference of 100 volts or thereabouts, the E.M.F. absorbed by the arc itself being 75 or 80 volts, the remaining 20 or 25 volts being used up partly in the lamp coils, but more particularly in the unusually large steadying resistance. The fact that the lamp can be thus joined up is a decided advantage, as it allows single lamps to be employed, or even to be joined in parallel with incandescent lamps, but the power which is dissipated in the steadying resistance, which must be of a high

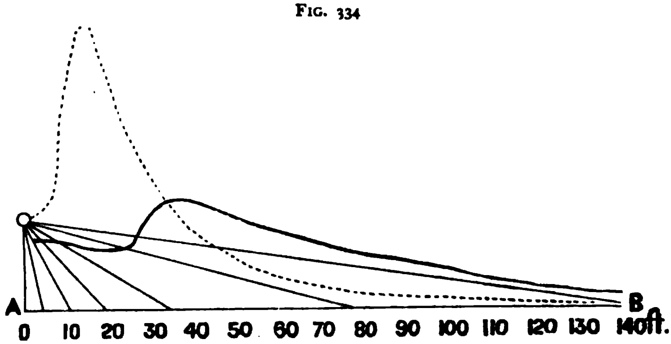
value because of the great variations in the resistance of the arc, is considerable and reduces the commercial efficiency. On the other hand, the life of the carbons is considerably enhanced by the fact that there is very little consumption due to combustion. The lamps can in fact be made to run for 100 hours or even more without retrimming, but, in order to permit of this, only really good carbons can be used, otherwise the impurities are volatilised and re-solidified on the inner surface of the globe. When this is allowed to happen it is obvious that the luminous rays are absorbed and the effective luminosity of the lamp is materially reduced. It is on this account that manufacturers usually urge that the globes should be frequently cleaned, but the student will doubtless realise that if time has to be spent in cleaning the globe the advantage which would otherwise result from long burning hours is seriously discounted, for if a lamp has to be attended to for cleaning purposes it would occupy very little longer time to re-carbon it, and an ordinary open arc might almost as well be used. As a matter of fact, the average enclosed lamp is materially less efficient than the open arc—that is to say, the amount of light is smaller in proportion to the power absorbed. There is one great advantage attending the enclosed arc, viz. that the increase in the length of the arc, which ranges from a quarter to half an inch, considerably reduces the screening effect of the negative carbon, but even this advantage is lessened by the fact that, as there is little or no chemical combustion, the ends of the two carbons are practically flat, and this absence of the tapering to which we are accustomed with open arcs means that the reduction in screening is much less than would otherwise be the case.

FIG. 333



In this connection the student should turn to figs. 326 and 327, and compare them with fig. 333, which is the polar curve for a Jandus enclosed arc lamp tested by Professors Houston and Kennedy. It will perhaps be noticed that the illumination is at its maximum intensity through a zone about 40° in width, which is considerably larger than that obtained by an open arc. This explains the fact that the illuminated area is enlarged, and although some allowance should be made for the special conditions under which the lamp was tested, fig. 334 may be taken as approximately indicating the distribution of light from open and enclosed lamps. In this figure the dotted line represents, by its height above the ground line A B, the relative illuminations up to a distance of

FIG. 334

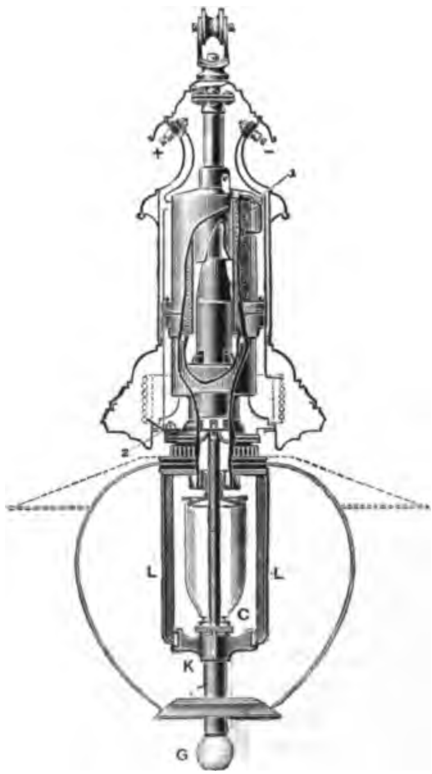


140 feet from the base of a standard supporting an open lamp 20 feet above the ground. Similarly the full line represents the illumination due to a Jandus enclosed lamp. It is, however, essential that, in order to obtain results such as those indicated, the globe should be quite clean, the adjustment perfect, and the arc steady. As a matter of fact, the lamp is often wanting in steadiness. The large area of the end of the positive rod prevents the maintenance of a definite crater, and as a consequence the arc travels round the carbon or from side to side, and the effort to produce a true crater being thus continually thwarted, the illumination is wanting in uniformity. It is largely on this account that a somewhat dense globe, and in many cases an

inner and an outer globe, have been resorted to, with the object of rendering the variations less apparent.

As we have said, the carbons are consumed very slowly, a lamp which will burn for 140 hours or thereabouts being fitted with a pair of 13-millimetre solid carbons 12 and 6 inches in length respectively, and although it is usually constructed on the non-focussing principle, *i.e.* with the lower carbon fixed, the rate at which that carbon is consumed is so slow as to give the lamp practically all the advantages of a focussing lamp.

FIG. 335



The Jandus lamp is the most prominent of the enclosed type, and the construction of one form of the lamp is illustrated in fig. 335.

The upper portion of the lamp, through which the upper or positive carbon is fed, is practically air-tight; the arc itself is enclosed in a small and almost air-tight glass cylinder, and the outer globe is supported at the top from the lamp itself, the access of air at this part being prevented by clamping the globe in asbestos washers. An inverted brass dish is pressed against the lower portion of the globe and prevents the air passing in at that point. The object is to limit almost to the point of exclusion the access of air to the arc, for reasons which have already been

explained. The only moving part, when the lamp is burning, is the core of the electro-magnet with its pole-piece and attachment which in moving up and down raises or releases the upper carbon, as the case may be. The negative carbon is fixed into a stationary holder which is supported by the frame L L. The negative holder in its turn supports the small opalescent cylinder C.

Resting on the top of this cylinder is a light steel cap provided with a hole just large enough to allow the upper carbon rod to pass freely. The lower end of the negative holder also carries the inverted brass dish referred to above, the upper face of which is pressed against the lower portion of the outer globe by means of a spiral spring. This arrangement effectually prevents air getting into the globe, but allows some of the gas contained therein to escape when the pressure is sufficient to overcome the spring. The positive carbon slides freely between a set of centring rings. By giving a slight twist to the knob G the spider K is released from the brass framework L and the glass cylinder C can then be withdrawn for cleaning and trimming. The hand hole thus provided at the bottom of the outer globe is sufficiently large to permit the inside of the globe to be cleaned, and there is therefore no need to dismantle the globe or any other part of the lamp. The lamp is differentially wound, the series and shunt coils being both wound over a thin tube, at the upper end of which is a massive pole-piece of soft iron with a slightly tapered hole turned out; this pole-piece is continuous with a stout sheathing of iron tubing, outside the coils. A box is secured to the lower end of this tube, and fitting into it, sufficiently closely to form an effective dashpot, is another box. The inner face of the latter box, which is attached to the central rod carrying the upper carbon, is inclined and carries a substantial soft iron armature which forms the core of the electro-magnet and which is tapered at its upper end to correspond with the inside taper on the upper pole-piece M. There are three slots cut in the armature, and a similar number of brass rings rest on the inner or inclined face of the box. These rings are not in any way attached to the core or to the box, so that when the current passes through the series coil, and the core is drawn up in the effort to complete the magnetic circuit, the box is also lifted,

and as it rises it presses the rings against the loosely fitting carbon rod. In this way the carbon is also raised, and the arc struck.

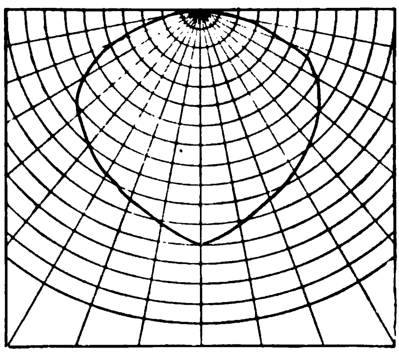
Every care is taken to ensure that the lamp shall be capable of withstanding abnormal voltages without risk of injury. This means that the insulating materials employed are of the best, and that the cross-section of the wires and other conductors must be ample. The coils are, as we have said, sheathed with iron, and there is some justification for the claim that the lamp is 'iron-clad.' The lamp described is obviously constructed for direct-current working, but a modification has been designed for alternate-current working, in which the two coils are wound over a laminated core, which by means of geared pulleys lifts a clutch mechanism for striking the arc.

In a development of the enclosed arc-lamp there are two pairs of carbons which are joined together in series, so that a single lamp can be joined across a pair of mains having a potential difference of from 200 to 250 volts. The light is, of course, about doubled, so also is the power absorbed. It is essential that the two arcs should be struck automatically and simultaneously. This is accomplished by means of a self-adjusting clutch arrangement.

A still more recent type of lamp than the enclosed is that known as the Flame type. In its construction it is a somewhat natural development of one of the very earliest of modern arc-lamps, viz. the Lampe Soleil, in which the two carbons which were, however, unusually stout, were inclined one to the other in the same vertical plane with a small slab or block of white marble immediately over the point where the two carbons met. The inclination of the carbons was in the form of a wide letter V, so that both rods were above the arc, which on being struck made the marble white hot. The addition of the light emitted and reflected by the marble to the light projected downwards by the arc itself, added to the absence of any screening effect of the negative carbon, resulted in the production of a very powerful light. The details of construction were, however, very crude, and the lamp was therefore a failure. In the modern flame lamp we have all the good features of the Lampe Soleil, but with the added

advantages of good constructional detail and a considerably increased length of arc. The pressure which such a lamp requires when burning pure carbon, and under the best conditions, is, owing to the increased length of the arc, about 90 volts, with a current of 8 or 10 amperes. The power absorbed is therefore approximately twice as much as in the case of the ordinary arc lamp. In this connection reference should be made to fig. 336, which is a polar curve constructed by Professor Wedding from experiments which he conducted with a lamp of this class. The curve is very instructive and should be compared with that given in fig. 326 for an ordinary open arc. M. Carbone is to be credited with having done good work in the development of the long flame horizontal arc.

FIG. 336



A further advance has lately been made by impregnating the carbons with various salts, which in combustion give to the arc a very large flame and one which is rich in luminous rays, instead of the small flame consisting almost entirely of the ultra-violet or non-luminous rays, which is so characteristic of the arc between pure carbons. The coloration of the flame can be varied from a pale yellow to a decided red by varying the composition of the impregnating salts, and although in many cases the colour is objectionable, the lamp can be made to emit a light which is warm in tone and more cheerful than that usually associated with the combustion or volatilisation of pure carbon. Mr. Trotter has remarked in connection with the introduction of luminous flame lamps that 'it is as though for many years we had been accustomed to nothing but non-luminous flames, like Bunsen flames or water-gas flames, and then somebody discovered the carburetted flame like that of ordinary gas-light. The flame of the arc lamp has been almost as useless for illumination as a Bunsen flame, but now someone

has succeeded in imparting a colour to it—and a very horrible colour I think it is.'

A great variety of substances has been experimented with, and as a result calcium fluoride has been found so far to be the most favourable, and it therefore forms in most cases the basis of a mixture for the core for flame-lamp carbons, a small percentage of potassium silicate frequently entering into the mixture. Bremer, who is largely responsible for the introduction of flame lamps, impregnated the entire carbon, but experience has shown that it is better to use a soft-cored carbon, even though the total diameter be small. The relative softness of the core assists in confining the arc to the extremities of the rods, and prevents to some extent the migration of the arc. This arrangement also has the advantage that atmospheric oxygen cannot get into contact with the impregnating salts and cause premature combustion and the consequent copious deposit of residue upon the inner surface of the globe. The softness of the core is, however, a term which is frequently misunderstood. The term does not mean a core consisting of a substance which is physically soft—or shall we say pliable or ductile, like jelly or lead? —but one which contains salts which have a low 'boiling point' or a low temperature of volatilisation, and which therefore require a lower voltage to establish an arc. Mr. Duddell, in the course of his experiments, has found that a carbon rod with a core consisting of a glass rod (which is composed largely of sodium silicate, and is therefore readily volatilised) enabled him to maintain an arc with a very much lower voltage than would have been the case had the carbon 'tube' been provided with an ordinary carbonaceous core. It is interesting to note that when the supply of 'impurities' is excessive the arc is irregular and the vaporisation causes continual bursts of light of a disagreeable character. The cored carbons usually manufactured are of relatively small diameter and contain not more than 10 per cent. of the incorporated mineral substances. The smallness of the carbons results in a correspondingly high current density, and it also follows that they are quickly consumed and require therefore frequent renewal. It will furthermore be readily seen that they offer a considerable electrical resistance, a feature which has led to a proposal

to reintroduce the practice, long since abandoned, of coating the carbons with an electrolytic deposit of copper. As it is, there is always a considerable amount of ash from chemical carbons, and the addition of the copper would result in the necessity for more frequently cleaning the globes. The admixture of 'impurities' in the core has the effect of reducing the temperature of the crater, and as a consequence its intrinsic brilliance is also lessened by something like 30 or possibly more per cent.; but the luminosity of the flame more than compensates for this loss, and the illumination per watt is undoubtedly very much greater than with the ordinary arc. It has been estimated that the intrinsic brilliance of the flame is about one-third of that of the crater, but of course very much depends upon the dimensions of the flame, and bald statements of this character can only be regarded as applying to particular cases. M. Blondel estimates that, with a continuous current service, equal mean spherical candle-powers result when the ordinary open arc takes three times the power required by a continuous current chemical flame arc—that is to say, the flame arc has three times the efficiency of the ordinary open arc, but against this must be set the enhanced cost of the carbons and the increased cost of trimming, which will appreciably reduce the difference.

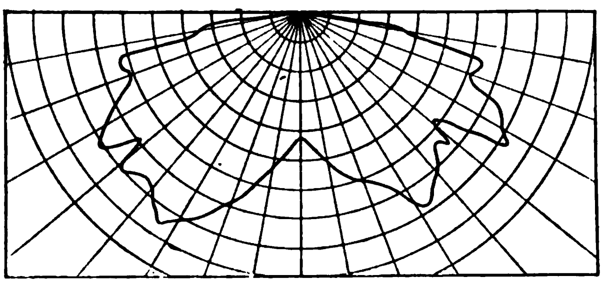
One advantage resulting from the adoption of the flame arc is that a smaller current may be used, so that while an open carbon arc usually absorbs 500 watts, a flame arc can be satisfactorily maintained with 250 to 300 watts. This is a greater advantage than would at first sight be apparent, the point being that in very many comparatively small establishments the possibility of having two illuminating centres instead of one would be a determining factor in deciding upon the adoption of lighting by means of the electric arc. On the other hand, the fact that the flame arc is usually shielded by an 'economiser,' that is to say, the arc is struck in a cavity in a piece of porcelain, there are few or no horizontal rays, and the bulk of the light is projected downwards. This will be clearer if fig. 337 is studied, which is the polar curve drawn by Professor Wedding for an open flame arc; it should be compared with fig. 336. The curve is decidedly irregular; with a good and well-adjusted arc the

curve should more nearly approach the formation illustrated in fig. 336.

The introduction of the economiser referred to above conserves the heat and, as Mr. Cowan points out, the effect is a tendency to enlarge the crater and thereby to increase the generation of luminous rays.

An enclosed chemical flame arc is at present impracticable owing to the fact that the underlying principle of the flame arc is combustion by oxidation, and obviously such oxidation cannot take place in an atmosphere devoid of oxygen. As we go to press, however, we learn that the Jandus Company have produced what they call a regenerative flame arc lamp. A smaller proportion of salts is used, and the carbons are arranged co-axially—that is,

FIG. 337



vertically one over the other. The positive carbon is placed in the lower holder, and the arc is surrounded by a clear-glass cylinder which is open at both ends. A pair of large curved tubes connect the upper and lower ends of the cylinder, passing down on the outer side of an outer glass globe. The products of combustion in the arc pass upwards, and, entering the two tubes, are forced down them and made to re-enter the cylinder at the lower end. The combustion is therefore more complete, and the particles are raised over and over again to a state of incandescence. It is said that the arc is one inch in length, that a pair of carbons will last for seventy hours, and that the current required is 5·5 amperes at a pressure of 100 volts. The electrical mechanism is very simple. The series and shunt coils are wound on separate

bobbins placed one on each side of the central tube which carries the upper or negative carbon. The cores of these coils slide up and down according to the current, and are connected together by a link which is pivoted to the frame of the lamp and is also connected to the negative holder, which is therefore raised or lowered as the series or shunt coil predominates.

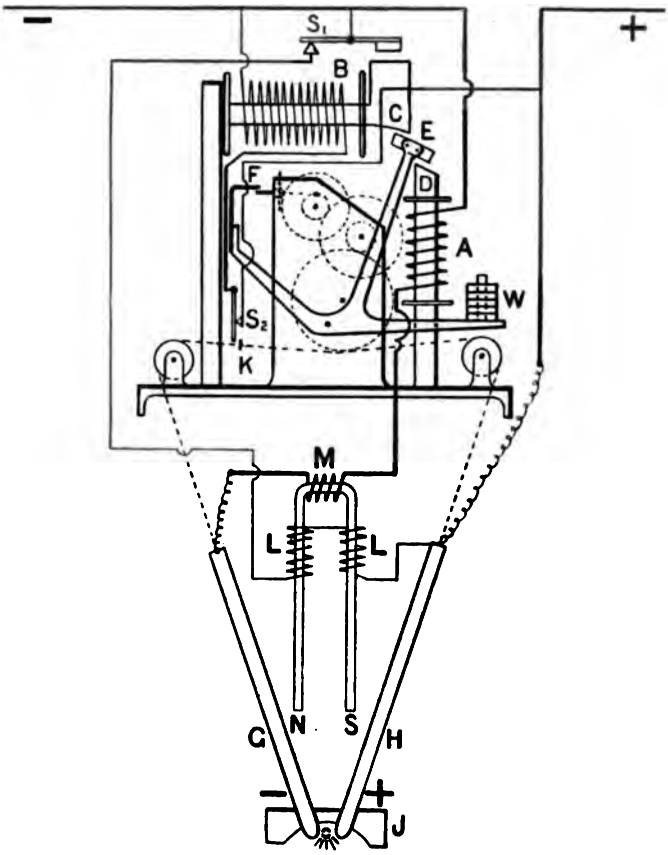
It will probably have occurred to the student that with inclined carbons the ascending column of heated air would tend to drive the flame upwards, so that the crater would be transferred to the upper edge of the carbon tip. In such a case the arc would be largely obscured by both the positive and the negative carbons, and in order to keep the arc as low as practicable it is usual to place a magnet with its poles just above the arc, with the result that the magnetic field repels the field due to the passing current and so drives the arc downwards. The application of this principle will be seen in the construction of the lamps which are described in the succeeding pages.

The patent granted for the Bremer lamp covered the essential principles of the chemical flame arc, but the lamp itself was imperfect in certain details, and has consequently been subjected to fierce competition.

Undoubtedly one of the most successful lamps of this type is the Excello. It is a well-designed and well-finished lamp, and is therefore capable of withstanding prolonged and heavy usage. The principal constructional details of the direct-current lamp are indicated in the diagram fig. 338. It is a differential lamp, and the series coil A and the shunt coil B are wound on separate cores placed at right angles with one another, the series coil or magnet being arranged vertically, and the shunt magnet horizontally, the latter being joined to the lamp terminals so as to form a shunt across the series coil as well as across the carbons, &c. Between the adjacent and peculiarly shaped pole-pieces, C D, of the two magnets is an armature E, which can swing to and fro, and is connected to a detent F, which, by means of a star wheel with which it engages, controls the feeding gear, consisting of a small train of wheels and chains attached to the carbon rods G H. One turn of the star wheel results, therefore, in a certain definite feed forward of the two carbons. The spur reduction gear for controlling the

feed has been found to give good results, both in the simplification of the constructional details and in the consequent cost of maintenance. The star wheel and detent may, perhaps, be

FIG 338



regarded as the successor to the rack rod of the older type of lamp.

Returning to the figure, it will be seen that when the shunt magnet B is predominant, the detent F is drawn away from the

four-vaned star wheel, and thereby frees the gear and allows the carbons, G H, to feed together. In the actual lamp the detent F is attached to the crank which carries the armature E, by means of a hinge, so as to give it a slight motion and prevent it from locking with the outer portion of one of the vanes, and to enable the one to slide over the other and ensure perfect locking at the proper time.

Normally the carbons are separate when no current is passing, the armature E being, by means of an adjustable weight, W, drawn down towards the pole-piece D, so that the detent F is engaged with the star wheel. At the moment that the current is switched on, the circuit through the series coil A is therefore broken, and the magnet B is alone effective, so that E is raised, F is withdrawn, and the carbons are allowed to feed. There is, however, a vertical rod (not shown in the figure) attached by means of a ball joint to the crank lever; when E approaches C, this rod is raised, and actuates a small slider at its lower end in such a way as to bring the carbons into contact. The circuit through the series coil A is thus completed, and the carbons being in contact, a heavy current flows through it, sufficient to draw the armature E down. This causes the vertical rod to fall and the slider to separate the carbons, and thereby strike the arc. The slight movement of the crank lever causes simultaneously a slight rotation of the drum which carries the chain attached to the upper ends of the carbon holders, so that the carbons are also raised through a short distance. There is thus a combination of lateral and vertical movements of an original and ingenious character. Subsequently the reactions of the series and shunt coils suffice to maintain an arc of almost uniform length. There are, however, one or two other points of interest which deserve attention. Immediately above the point where the carbons converge and form the arc is an 'economiser,' J, which consists of a circular block of a particular class of porcelain, and performs the same functions as the block of marble in the Lampe Soleil previously referred to. The arc being situated within the recess on the under side of the economiser is protected from possible draughts of air. The economiser is supported in a ring which is [illegible] to a stout metal base, so constructed as to separate the [illegible]

globe from that in the cover, and thereby to prevent the products of combustion from getting into and clogging the works.

The angle at which the carbons are inclined to each other is so sharp that there is the risk that when the carbons have burned their full time, and consequently do not feed further forward, the arc itself may travel up, with the result that the economiser might be fractured and some of the metal work destroyed. In order to prevent this a cut-out device is provided for circuits carrying pressures up to 125 volts. When the carbons are in almost their lowest possible positions, and cannot feed further, the shunt circuit is automatically broken by a carbon-faced switch S_2, mechanically operated by a small detent, K, attached to the chain which connects the two carbons. This causes the series magnet to suddenly draw the armature, E, right over, and, by separating the carbons to the maximum distance, to effectively break the arc. When a higher voltage, say 240, is employed a blow-out magnet, N S, is fitted. This is partially excited, so long as the lamp is running normally, by a series winding, M, the circuit for which passes from the negative carbon holder to the series coil. When, however, the shunt circuit through the coil B is broken, and the pole-piece, C, is demagnetised, an extra shunt circuit is provided from the positive terminal through the coils L L and the switch S_1, which largely increases the magnetisation of the blow-out magnet, and infallibly extinguishes the arc. Bearing in mind the reactions of the series and shunt coils, the student will perhaps realise that, it being granted that the proper position of the arc is just within the cavity of the economiser, an arc formed below the edge of the economiser indicates that the potential difference is too small and that the steadying resistance in series with the lamp requires to be reduced. If, on the other hand, the arc burns high up in the cavity, the series coil is too effective, or, in other words, the potential difference is excessive, and the steadying resistance should be increased in order to restore the balance.

The lamp is well and substantially made, and all the parts are standardised, so as to be capable of easy replacement in case of need, as so much depends upon the proper adjustment of the lamp. This portion of the work is always attended to before the

lamp is handed over to the mercies of the lamp-trimmer, and the adjustment having been once made the lamp is sealed, a proceeding which bespeaks a certain measure of confidence by the manufacturers in the reliability and permanency of their work.

A feature in connection with the Excello lamp, and probably with all others burning impregnated carbons, is that the same class of carbon should always be used in the same class of lamp. As we have already said, they are small in diameter, the 10-ampere Excello lamp taking 10- and 9-millimetre carbons for the positive and negative respectively, while the more frequently employed 8-ampere lamp takes carbons of 9 and 8 millimetre diameter. The rate of consumption is such that for a 10-hour run the length of the carbons is 15¾ in., while lamps constructed to burn for 16 or 17 hours require a length of 23½ in. The resistance of the carbons is therefore a material factor, although in the class in question each rod is provided with a thin metallic core which reduces the loss of pressure in a pair of the longer carbons to about 4 volts, as compared with 12 volts or more in certain others.

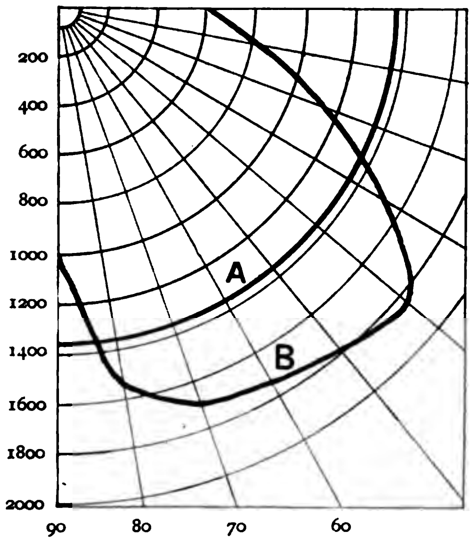
Fig. 339 is instructive. It contains a polar curve, B, constructed by an independent testing institution, as the result of a series of tests. The shape of the curve is very interesting and indicates a steady arc; the reduction in the illumination immediately under the arc is probably due to the fact that in that position the rays are due to the flame alone. The curve A is an average of the tests taken below the horizontal $x y$, and is therefore the mean hemispherical candle-power curve, and the tests showed that this mean hemispherical candle-power (or M.H.C.P.) for a lamp taking 8·7 amperes with a potential difference across the arc of 44 volts, and burning 9 and 8 millimetre carbons, was 1352, or about twice the value for an ordinary 10-ampere open arc lamp, both lamps being fitted with globes.

The 'Oriflamme' arc lamp is another successful form of lamp in which the carbons contain within their cores mineral salts, and it has also the exceptional feature that, in order to obtain a length of burning with this class of carbon which would not otherwise be possible, it is constructed with magazines or storage chambers to contain several pairs of carbons to be successively

consumed. The lamp is therefore designed on novel lines, and its construction and action are fully illustrated in figs. 340 and 341, which are similarly lettered.

The internal framework of the lamp is of a substantial construction. The terminals at the top of the lamp are so arranged as to secure the framework into the top casting and at the same time insulate it from the outer casing of the lamp. In continuous-current lamps, the framework, in addition to serving as

FIG. 339

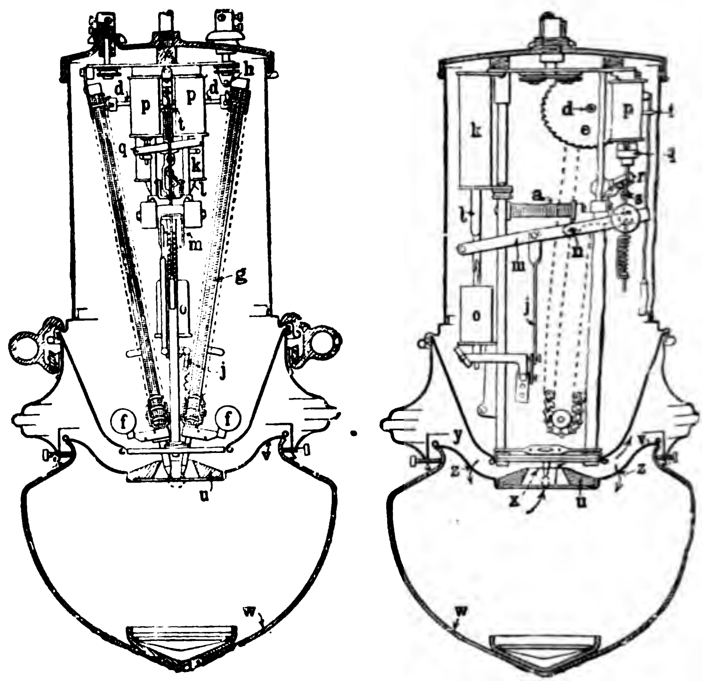


a support for the regulating coils, magazines, &c., is employed for the purpose of inducing a magnetic field in the neighbourhood of the arc for repelling it downwards. The two downwardly extending limbs of the framework, terminating at a point just above the arc, form the poles of an electro-magnet excited by the main current flowing through a coil, *a*, placed horizontally towards their upper ends. The framework forms the positive pole of the lamp.

The carbon magazines consist of flat receptacles in which the carbons are contained one behind the other. Provision is made

at the back of the magazines for inserting the carbons. Spring arms, *b*, bear upon the carbons and keep them pressed up to the discharging side of the magazines. Projections, *c*, on endless chains capable of rotation engage with the carbons for advancing or feeding them from the magazines as is required. As each pair of carbons is fed forward, others are pressed into position by the

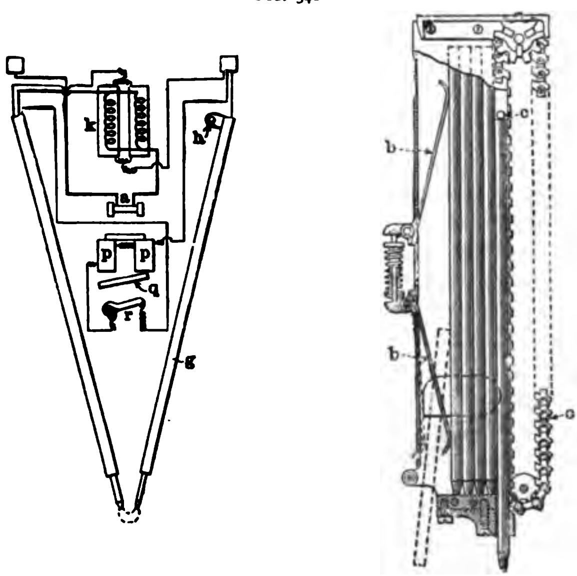
FIG. 340



spring arms, to be engaged in turn by further projections on the chains. The feeding chains run on pulleys fixed at each end of each pair of magazines, and motion is transmitted to them simultaneously through a shaft, *d*, engaging with the top pulleys of each magazine which is revolved by means of a pawl engaging with a ratchet wheel, *e*, mounted upon the shaft. As each carbon issues from the lower end of each magazine it passes through

a weighted clutch, *f*, which serves to convey the current to the carbon as well as for retaining it in position. The carbons meet to form the arc just below these clutches, as the magazines are disposed to each other in the form of a letter V. In order to strike the arc after the carbons touch and the current passes between them, the negative magazine, *g*, is loosely pivoted at its upper end (*h*) in a bracket fixed to, but insulated from, the framing, and is caused to swing away from the other or positive

FIG. 341



magazine, which is rigidly fixed and is uninsulated from the framework of the lamp. The movable magazine is connected by means of a bell crank lever and link, *j*, to the regulating mechanism from whence it derives its movement.

The regulating mechanism consists of a pair of solenoids, *k*, mounted side by side on the framework at the back of the magazines and having a horseshoe iron core, *l*, working within them. Each solenoid consists of a high resistance winding, which constitutes the shunt coil across the arc, and of a few turns

of low resistance wire wound in opposition to the shunt coil, and constituting the series winding, through which the main current passes. The movable core is pivoted on a 'knife edge' bearing to a rocking cradle, *m*, which in turn is also pivoted on 'knife edges,' *n*, to the framework. The link which conveys the movement from the regulating mechanism to the swinging magazine is pivoted upon this cradle, so that a movement of the regulating core is directly conveyed to the ends of the carbons projecting below the magazines. Coming now to the action of the regulating mechanism: before the current is switched on, the ends of the two carbons are apart and the core in the solenoids is at its lowest position. When the current is switched on, the shunt coil is strongly energised and causes the core to be attracted. This motion at once brings the carbons into contact, and a current flows between them simultaneously with a drop of voltage across them, and the current in the shunt coil being consequently weakened, while the current in the series coil is strengthened, allows the movable core to drop and therefore to separate the carbons and strike the arc. The magnetic pull of the regulating solenoids upon the iron core maintains a state of equilibrium or balance, and keeps the arc at its correct burning voltage. The reverse end of the rocking cradle to which the core is attached is suitably weighted to obtain a balance corresponding with the voltage of the arc it is desired to maintain. As the carbons are consumed, the regulating gear gradually moves one magazine towards the other one, until when no further movement is available it is necessary to feed the carbons from the magazines in order to further maintain the arc. The rocking cradle when near the limit of its movement as above described brings into the action the magnetic feeding motor as and when required to feed the carbons from the magazines. Just below and attached to the core by means of a socket is an air 'dashpot,' *o*, provided to steady or damp any sudden, violent movement which might otherwise result in the lamp 'pumping.' This dashpot, for cleaning purposes, is made readily detachable from the lamp by loosening a thumbscrew.

The magnetic motor is brought into action by the regulating gear, and its purpose is to rotate the ratchet wheel and shaft

connected with the chains of the two magazines so as to feed the carbons from them. The motor consists of a horseshoe electro-magnet, *p*, provided with a loosely pivoted iron armature *q*. The magnet is excited by a small current drawn from across the lamp terminals, and in circuit with it is a make and break switch, *r*, which is normally in the 'off' position. The switch is provided with links, *s*, both connecting with the regulating cradle and with the armature. The cradle by its movement closes the switch, and the armature when it rises, being attracted by the poles of the magnet, opens it again and allows the armature to fall. The armature being provided with pawls, *t*, engaging with the ratchet wheel as above mentioned, by its reciprocating action causes rotation and consequently a feed of the carbons from the magazines.

The make and break switch, in order to prevent the possibility of dirt or of any deposit from the arc affecting its reliable working, is totally enclosed in a vacuum within a small glass tube provided with platinum leading-in wires at each end for the terminals. One end of the tube is enlarged and contains a small quantity of mercury, the tube itself being pivoted in the lamp. When the tube is tilted by the regulating cradle the mercury runs from the bulb along the length of the tube, making electrical contact between the two terminals, and when the armature is raised the reverse action takes place and contact is broken. In order to prevent a possible breakdown of the insulation on the magnet winding, due to a sudden and excessive rise of potential on breaking this circuit of high self-induction, a sparking gap is provided as a protection. The copper connecter fixed on and insulated with mica from one of the lower cheeks of the magnet in its enclosed portion serves this object.

The globe, reflector and ventilating arrangements of the lamp are shown in the illustration in section. The porcelain reflector, *u*, is provided with a plate, *v*, which closely engages with the top and only opening of the globe, *w*. The inside of the globe is freely connected with the space above the plate *v* by means of the central passage, *x*, in the porcelain reflector through which the carbons project and in which the arc is struck. The upward draught created by the heat of the arc serves to carry away from

the globe through the central passage into the space y, the vapours of combustion which would otherwise settle upon the inner surface of the globe and obscure the light. This ventilation is facilitated by allowing a small supply of air to enter the globe through holes, z, in the reflector plate.

A glass and copper gauze tray placed at the bottom of the globe catches the short butt ends of the carbons which are not consumed as they are discharged from the magazines.

On continuous current circuits an adjustable resistance is, as usual, connected in series with the lamp or lamps to steady or regulate the current. On alternating circuits a choking coil is used for a similar purpose.

In the event of a lamp being temporarily extinguished during the changing of a pair of carbons, or from any other cause, a substitutional resistance, which is connected with an automatic cut-out across the lamp terminals, is arranged to automatically take the place of the lamp during the period of extinction in order that the other lamps in series with it may be kept burning, as well as to prevent any possible damage to the lamp due to an excessive rise in the voltage across its terminals. This apparatus is either fixed on the top of the lamp itself or in some other convenient position. The lamp when the magazines are fully equipped with carbons will burn for a period of from 40 to 50 hours.

CHAPTER XVI

INCANDESCENT LAMPS—PHOTOMETRY—DISTRIBUTION

FOR the lighting of the interiors of buildings, except in the case of certain large halls, railway stations and similar structures, arc lamps are unsuitable. For ordinary rooms the light would be too powerful, and for rooms where the total amount of light required is sufficiently large to equal that of an arc lamp, there would generally be an objection to the concentration of the whole of the light at a single point.

Fortunately there is a second class of lamp which is capable of meeting such requirements. It is the well-known incandescent lamp, and consists generally of a very thin strip or filament of the purest obtainable carbon wholly enclosed in a glass bulb from which the air has been carefully exhausted; the connection between the carbon and the external conducting wires being secured by short pieces of platinum wire fused through the glass. The passage of a sufficiently strong current through the filament causes it to be raised to a white heat, when it is, of course, intensely luminous. It may perhaps be advisable to discuss briefly the principles upon which such a lamp must be constructed before describing more fully the actual processes.

It was shown, when discussing the Cardew hot-wire voltmeter, that when a current of electricity is urged through a solid conductor, heat is developed, and that the amount of heat so developed is proportional to the total energy expended in the conductor. It was also shown that this energy is proportional to the product of two factors—viz. the strength of the current C, and the difference of potential E between the extremities of the conductor, necessary to maintain that current—or the heat H developed is proportional to E C; and, since by Ohm's law $E = C R$, therefore $E C = C^2 R$.

It is manifest from these simple formulæ that the heat developed varies directly as the resistance, and directly as the square of the current strength. If we have two equal and uniform conductors A and B, and maintain a potential difference at the ends of one of them, A, twice that at the ends of the other, B, the heating effect in the former will be quadrupled; for with equal resistances the current strength will also be doubled, and in fact energy is being expended four times as fast in A as compared with the rate of expenditure in B. If, however, while both conductors are of the same length and sectional area, the specific resistance of B is twice that of A, and the same potential difference is maintained in both of them, the resistance of B, being twice that of A, will halve the strength of the current flowing through B. Hence, if in A, H is proportional to E C, or C^2R, then in B, H is proportional to $\frac{1}{2}C\,E$ or $2R\left(\frac{C}{2}\right)^2 = \frac{1}{2}C^2R$. In this case twice as much heat is developed and twice as much energy is expended during a given time in A as compared with B. Again, if the current in B is made equal to that in A, by doubling the potential difference in the former, then in A, H is proportional to E C or C^2R, and in B, H is proportional to $2E\,C$ or $2C^2R$, so that doubling the resistance and keeping the current strength constant doubles the heat developed and causes twice the amount of energy to be expended. One great lesson is here again enforced—viz. that the amount of energy obtained in the form of heat can only equal and never by any possible means exceed the amount of electrical energy expended or absorbed in the conversion.

The relation between heat and temperature has already been discussed, but we must again refer to it here, as it is of the utmost importance. Let us suppose that, instead of employing a conductor of increased specific resistance, we experiment with two samples of the same material and of the same sectional area, but that one of them, B, is twice as long as A; then the resistance of B will also be twice that of A, and if equal currents are urged through these conductors, the heat developed in A will be only half that developed in B; but as B is twice the length of A, and has therefore twice as much matter in it, the temperature of the two conductors will be equal. Now when a body is made very hot it becomes

luminous, and the luminosity of a body is proportional to its temperature. In this experiment, therefore, the temperature of A and B being equal, the luminosity or intrinsic brilliance will be equal, although B absorbs twice as much energy as A, because its resistance is double. Moreover, as B is twice as long as A it will emit twice as much light. Now if the resistance of B is made double that of A by halving its sectional area instead of by doubling its length, and equal currents be urged through each as before, we still get twice as much energy absorbed, and therefore twice as much heat developed in B as in A. And since the mass, or the quantity of matter, in B is now only half that in A, equal quantities of heat would cause the temperature of B to be twice that of A; but, as twice the amount of heat is developed in B, its temperature is raised to four times that of A. This clearly indicates the direction in which we should work in order to raise a conductor to a very high temperature. Stated generally, a large amount of energy must be expended on a small mass of matter; therefore the conductor must have a high resistance, and in order to keep its mass small this high resistance must be obtained by diminishing its sectional area rather than by increasing its length, and further, the material chosen should be one which has a high specific resistance.

Men were not long in conceiving the idea of employing the heating effect of a current upon a conductor for illuminating purposes, and patents based upon this principle were taken out sixty or seventy years ago. But these early efforts were one and all of them failures from a commercial point of view, although some of them were almost identical with many of those of a comparatively recent date. It was seen that a conductor of high specific resistance was necessary, and this limited the number of materials available. This number was further reduced by the fact that most conductors either melt or volatilise at comparatively low temperatures —before, in fact, the temperature of white heat is attained. Iron, which is cheap and has a high resistance, and which might therefore be considered a suitable substance, unfortunately melts at a comparatively low temperature. It is for this reason useless as an illuminant. It also oxidises or combines with the oxygen of the air as its temperature rises. German silver is for similar reasons

not available. We were, until very recently, limited among the metals to the expensive platinum or its alloys. Platinum is capable of being raised to a bright white heat, and can then emit light of considerable brilliance. It has also the advantage of being practically inoxidisable. The critical temperature is, however, suddenly reached : that is to say, above a certain point a slight increase of temperature suffices to produce liquefaction and therefore to cause a rupture and so disconnect the circuit. It must also be remembered that the resistance of metals increases materially with an exaltation of temperature, a fact which hastens the fracture of the wire. Efforts have been made to prevent this overheating by means of automatic regulators, which short-circuit the lamp when the current reaches a certain predetermined strength, and so cut off the current just at the moment that there is a risk of breaking the wire. These are clever laboratory expedients, but nothing more. The possibilities of tantalum, wolfram, tungsten, osmium, and other of the rarer metals had not manifested themselves, although, as we shall see presently, considerable progress is now being made in the production of lamps with metal filaments. The fact, however, remains that if we had been restricted to metallic conductors, electric lighting by incandescence would long since have been given up as impracticable. Carbon, it will be remembered, is a non-metallic body, and it is a sufficiently good conductor of electricity for our purpose, but it has also the advantage that it has a considerably higher specific resistance than platinum. A remarkable feature pertaining to it is that its resistance decreases with an increase of temperature. It is a substance which cannot by any ordinary means be melted or volatilised, so that in these respects it is superior to platinum or any other of the ordinary metals. It, however, oxidises readily when heated in an atmosphere containing free oxygen, such as ordinary air. This difficulty was for a long time insurmountable, although many efforts were made to overcome it, such as placing the carbon under a glass receiver, and depriving the enclosed air of its oxygen by means of a piece of phosphorus, a substance which oxidises readily at ordinary temperatures ; and when all the oxygen has thus been converted into an oxide of phosphorus, the carbon remains suspended in an atmosphere of the remarkably

inert gas nitrogen. But such an arrangement as this was clumsy, and in fact impracticable. Even supposing it to have been otherwise, the carbon then procurable was very defective. Thin rods of graphite or gas-retort carbon, or sections of the artificially prepared material, were tried; they could not, however, be obtained of sufficiently small sectional area and were too irregular in structure to prove practically useful. Efforts were also made, and with a better prospect of success, to accomplish the object in view by placing the carbon in the then best obtainable vacuum. The vacua were for a long time far from perfect, and as a consequence the durability of the carbons was very brief; but when it was shown how it was possible to secure an all but perfect vacuum, a fresh impetus was given to the idea of lighting by the incandescence of thin pencils, or, as they were subsequently called, filaments of carbon. Since then, the real improvements that have been made have been in the formation and fixing of these filaments, which can now be prepared from almost any substance having a large proportion of carbon in its composition. As organic substances consist to a great extent of carbon, and as these substances can generally be decomposed somewhat readily, it is only natural that they should form the basis from which the filaments are manufactured. Carbon filaments were in the early days divisible into two classes: (1) those in which the fibrous structure of the carbonaceous body was retained, and (2) those in which the original or organic structure was altogether destroyed during the process of manufacture, and the material rendered thoroughly homogeneous. To the first class belonged the Edison filament, and to the second class the filaments of Swan and the majority of other inventors. It is a remarkable fact that Edison asserted that to give the carbon the highest possible resistance and the smallest tendency to disintegration it should retain its structural character. Swan, on the other hand, maintained that the structure of the material should be entirely destroyed, and the carbon filament made as dense and homogeneous as possible. Experience has shown that the latter filament is the better of the two.

It might have been gathered from what has already been said that the chief desiderata in a good lamp are: (1) that the filament

shall be sealed in an air-tight vacuous glass vessel; (2) that efficient means shall be provided for connecting the filament with the external circuit; (3) that the filament shall offer considerable resistance; (4) that it shall have a small mass, so that its temperature shall be raised as much as possible by a given quantity of heat; (5) that it shall be durable at high temperatures in a vacuum; and (6) that the lamp shall be capable of being manufactured at a small cost, and of any desired dimensions or resistance. It is the last of these requirements which gives the greatest trouble in meeting, because a slight variation either in the thickness or sectional area, or in the amount of radiating surface of the filament, causes a considerable difference in the luminosity.

The Swan filament was originally made direct from cotton thread, but it is now formed by squirting a solution of cellulose through a fine nozzle at high pressure, cellulose being the chief constituent of such vegetable substances as cotton, linen, paper, &c. The first process in the manufacture of a carbon filament consists in the preparation of the thread. This is accomplished by dissolving a high grade of cotton-wool in zinc chloride or other suitable solvent. This produces a kind of brownish gummy fluid, which is squirted as a fine thread into alcohol. The effect of the alcohol is to remove impurities, to harden the thread and allow it to be coiled at the bottom of the vessel without any risk of the convolutions sticking together. The washing in alcohol is continued for twenty-four hours or thereabouts, at the end of which the thread, or, as we may now call it, the filament, has assumed a gelatinous appearance, homogeneous and devoid of all structural formation. The next process is to remove the alcohol. This is done by prolonged washing with clean water, and the coils are then dried by being loosely wound on drums and exposed to the air. During the drying the filament contracts considerably, both in length and in diameter, and it is therefore necessary that the drum and the winding should be so arranged as to avoid the risk of rupturing or even of unduly straining the filament. It is then subjected to the process of 'carbonising,' or converting it into a solid carbon filament. It is in this process that the filament is definitely shaped. The thread is first wound on a former consisting of a round carbon rod and a rectangular carbon block fixed parallel to, but

at a short distance from, the rod. In order to make the loops characteristic of modern long filament lamps, the thread is turned twice or thrice round the carbon rod before being passed round the rectangular block to which the thread is secured, so that the ends of what will ultimately be a number of individual lamp filaments can be cut through and released. This permits of further contraction during the process of carbonising. A number of these formers is placed in a crucible until the vessel is nearly full. Powdered charcoal having been shaken over the contents to fill up any spaces that may have been left, the lid is placed in position and an air-tight joint is made. The crucible, being thus prepared, is placed in a suitable furnace and raised slowly to a white heat. The gradual increase of temperature is important in determining the shapeliness of the filament. Too rapid an increase in temperature might cause the threads to sag, so that the form of the filaments would be more or less distorted. As the powdered charcoal gets hot it absorbs any free oxygen that may be in the crucible, and thereby preserves the filament from oxidation. The high temperature is necessary to render the carbon hard and durable, to increase its conductivity, and to reduce its capacity for holding atmospheric and other gases within its pores. This last-mentioned feature is not only interesting, but it is also of considerable importance. Most substances are more or less porous, and have the power in varying degrees of holding gaseous particles within those pores, a power or property known as occlusion. As the temperature of a body rises these gaseous particles expand and may force themselves through the substance, frequently causing minute fissures; with some substances, such as carbon in its ordinary form, this power of occluding gases returns with a resumption of the normal temperature. It is, therefore, imperative that the nature of the filament should be so altered as to prevent, as far as possible, this taking place. Hence the necessity for thorough carbonisation at a high temperature, and as a result of the process the filament is reduced in size, is definitely formed or shaped, and is converted into a thin elastic carbon, with a black but shining surface.

This alteration in character of the carbon is continued in the next process, which is that of 'flashing.' Before proceeding

with this process, however, the filaments are cut to about the desired length, sufficient margin being allowed for making connection with the platinum wires, which pass through the bulb to the external circuit. The filament is then suspended in an atmosphere of some hydro-carbon, such as benzene vapour, and traversed by currents sufficiently strong to raise it to a considerably higher temperature than was practicable during the carbonising process. The effect is partially to decompose the gas, and to cause a deposition of carbon particles on the surface of the filament, the result being that the carbon is hardened, the conductivity increased, and the power of occlusion eventually destroyed. Should there be any weak spots in the filaments they will be raised to a higher temperature than the rest, and a more copious deposition of carbon will take place, until uniformity is attained.

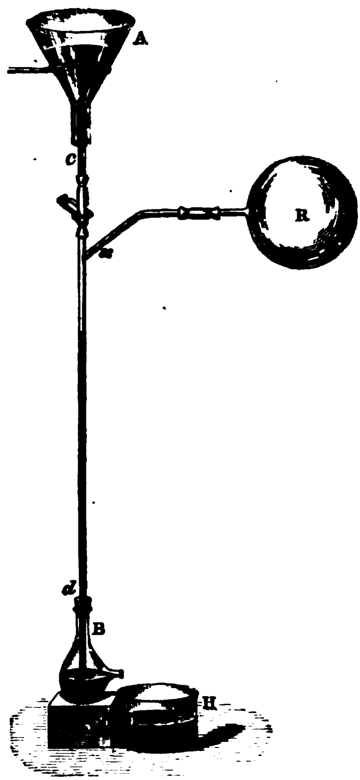
Platinum wires are always employed in mounting the filaments, as platinum is the only metal which has a coefficient of expansion nearly equal to that of glass: that is to say, it expands or contracts with variations of temperature at almost exactly the same rate as glass, so that it can be fused into that material without any risk of its subsequently fracturing the glass on cooling, or retreating from it to such an extent as to allow air to pass through. The coefficient of expansion for white glass is 0·0000086, while for platinum it is 0·0000088, so that these two substances agree very closely in this respect. The coefficient for wrought iron is 0·0000122, or about 50 per cent. higher than that for glass, while for other metals the disparity is still greater. Many efforts have been made to find a substitute for platinum, but they have all proved fruitless. The anxiety to find a substitute arises from the scarcity and consequent high price of platinum. This is the only objection, for in all other respects it answers admirably; at the moment of writing it is dearer than gold. The supply is derived almost entirely from Russia.

The connection between the carbon and the platinum is made by flattening out the ends of the wires into minute plates, which are then bent gently round the ends of the filament. The joints are perfected by immersion in a hydro-carbon liquid, such as benzene, the filament being short-circuited, and the joints raised to incandescence by a strong current, causing a decomposition of

the hydro-carbon, and a deposition of the carbon upon the joints. As a consequence good electrical connection between the metal and the carbon is obtained.

The two pieces of platinum having been fused into one end of the bulb, and the opposite end having been drawn out to a fine tube, the embryo lamp is ready for the next process, viz. that of exhausting the bulb of its contained air and moisture. This has to be performed carefully, and it is here that some of the greatest difficulties are met with.

FIG. 342



The vacuum obtainable in an ordinary mechanical air-pump is, as we have already indicated, far from perfect, and unless supplemented by other processes is useless for the purpose. There are, however, mercurial air-pumps which are so far superior to the mechanical form that they can produce even higher vacua than are actually required for lamp-making, and until recent years modifications of the Geissler and more particularly of the Sprengel pump were in general use, and even at the present time pumps of the latter type are in use for special purposes.

The fundamental principle of the Sprengel pump is illustrated in fig. 342. It consists of a stout glass tube, *c d*, 39 or 40 inches long, with a branch *x* connected to the vessel (such as a lamp bulb), R, to be exhausted. A large funnel-shaped reservoir, A, supported by a stand, is connected to *c d* by means of a piece of

indiarubber tubing, the size of the channel through it being adjustable by means of a pinch-cock. The lower end of *c d* dips below the surface of the mercury in the flask B, which is furnished with a spout a little higher than the bottom of *c d*, in order to allow the mercury to pass out into the reservoir, H. The pinch-cock is so adjusted as only to allow the mercury to pass down the shaft a drop at a time. Each drop constitutes a plug or piston, which fits closely to the sides of the glass, and in its descent drives before it any air that may happen to separate it from the drop beneath it. The shaft *c d* is to all intents and purposes a barometer, so that the drops of mercury accumulate until a column is formed about 30 inches high, the actual height depending upon the counter-pressure of the outer air at the time being. Hence the distance which the mercury pistons ultimately fall is only 9 or 10 inches. It will be evident that as the drops fall, and tend to establish a vacuum above them, the air in R expands and part of it occupies this otherwise vacuous space. Consequently, as each piston passes the junction of *x*, the air is swept out little by little until finally a very good vacuum is obtained in R. When the degree of rarefaction becomes considerable, the pistons fall smartly upon the column of mercury and give out a distinct metallic ringing sound. This hammering frequently sets up such strong vibrations as to fracture the glass; and it is this which limits the length of the shaft. As the mercury falls on the barometric column, an equal quantity is, of course, driven out at the lower end, carrying with it also the bubbles of air which separate the little plugs. The mercury collected in H is replaced in A as necessity arises. This process is obviously very long and tedious, but the exhaustion can be materially hastened by employing a good mechanical air-pump to exhaust the system as far as possible by mechanical means, the process being afterwards completed with the mercury pump. A barometer gauge can also be used to indicate, by the height of its contained mercury, the degree of exhaustion obtained. There were many difficulties to be overcome before the mercury pump could be made into a practicable factory tool, and these were dealt with at some length in the earlier editions of this work. The present-day process consists for ordinary lamps in the provision of a sufficiently good

vacuum by means of a special form of mechanical pump of what is known as the Fleuss type, which can be worked by power, and which is therefore much cheaper in action.

The lamp having been sufficiently exhausted, the small glass tube connecting the bulb to the exhaust tube is fused, drawn out to a thread, and the lamp sealed off.

Although it is, evidently, a comparatively simple matter to obtain the degree of exhaustion necessary for incandescent lamps, there are several causes for a deterioration manifesting itself in the vacuum after the finished lamp has been laid aside for a time, such as the occlusion of gases by the carbon and platinum, and by the deposit employed to connect them together. A very thin film of air is also liable to adhere to the inner surface of the bulb. In order to prevent these troubles it is in some places the practice to raise the filament to incandescence during the later stages in the process of exhaustion.

The vacuum is usually tested by means of an induction coil; one method is to fuse two platinum wires into a glass tube leading to the lamp, and exhausted simultaneously with it, and to connect these wires to the terminals of the secondary coil. The distance between the ends of the platinum wires inside the tube is so adjusted that when the required degree of exhaustion is attained the spark passes through the air outside the tube in preference to traversing the vacuous space between the platinum points. Another method, applicable to the finished lamp, is to connect one end of the secondary coil to the filament, and the other end to a loop of wire wound outside the bulb, the quality of the vacuum being determined by the relative feebleness of the discharge which takes place between the filament and the bulb.

When a lamp is badly or imperfectly exhausted the filament 'burns'—that is to say, it oxidises—and it also requires a greater amount of heat to raise and maintain its temperature at the required point, owing to the fact that the air particles carry a portion of the heat away by convection. One effect of this convection discharge is that the bulb gets perceptibly heated, sufficiently so to char flannel and suchlike materials.

Such are the general features pertaining to the construction

of the incandescent lamp. There are a number of ways i which connection is made between the lamp and the extern circuit, involving a corresponding variety in the form of the lamp holders.

Fig. 343 illustrates the method more generally employed for connecting the filament to the external circuit.

FIG. 343

The top of the lamp is provided with an insulated brass collar fixed with a cement consisting either of plaster of Paris or of a glassy material known as vitrite, the platinum wires attached to the filament being connected to the two brass segments embedded in the cement. The collar has two small pins, which fit into the 'bayonet-joint' holder shown in the figure. There are many varieties of this type of holder, but a sectional diagram of one of the best—that made by the Edison and Swan Company—is given in fig. 344. A perspective view of the electrical portion of the holder is also given in fig. 345. This part is mounted on a circular porcelain base held in the position shown in fig. 344 by a series of brass collars. Two holes are made in the base, and through each hole a connecting wire is passed, and clamped into a small brass contact block by means of a set-screw. This block is an extension of a small socket, which carries a brass spiral spring, the free end of which presses against a brass plunger and strives to keep it out as far as it will go, a small flange on its base preventing it from being wholly ejected. The two plungers with their sockets, &c., are, as shown in fig. 34[illegible]ted by a little S-shaped ridge of porcelain (made in on[illegible] base), which also shields the plungers from the [illegible]older. In twisting the lamp into the holder the [illegible]hing

contact with the two plungers, and the lamp is thus thrown into circuit by the mere act of fixing it in the holder; but as the free ends of the plungers are rounded, the contact between them and the brass segments in the lamp is comparatively small. This frequently offers sufficient resistance to develop an appreciable amount of heat with a consequent loss of energy, and the limited areas of the

FIG. 344

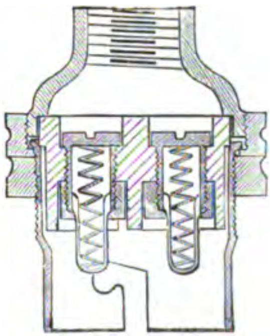


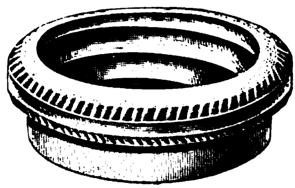
FIG. 345

FIG. 346

various contact surfaces in this form of holder render it unsuitable for high candle-power lamps—that is to say, for lamps taking a heavy current. It is, nevertheless, the favourite type for general work, and it is usually of much better manufacture and mechanical finish than its competitor, the Edison 'screw' holder, which is illustrated in fig. 346. In this case one end of the lamp filament is connected to the coarse screw thread stamped out of thin sheet

brass and set in plaster or vitrite, and the other end to an insulated brass stud projecting from the bottom of the lamp. This affords another means of throwing the lamp in circuit by the act of placing it in its holder, which is provided with a corresponding brass screw thread and a small brass disc mounted on a stiff insulated spring, which maintains contact with the stud on the lamp. The screw thread and stud in the holder are electrically connected with a pair of set-screws fitted in the body of the holder, and to which the external wires are attached. With good workmanship and substantial metal fittings, instead of the flimsy stampings usually employed, this should be an efficient holder. In fig. 347 is illustrated (full size) the porcelain ring which serves the double purpose of insulating the brass screw thread from the rest of the holder and of helping to keep the lamp in position. This porcelain ring frequently breaks, more especially under rough usage, and short-circuits have often been established in consequence.

FIG. 347



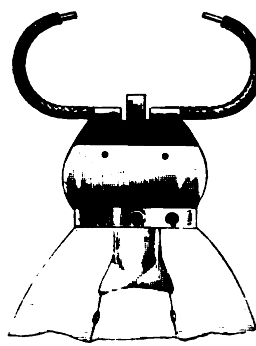
Lamp-holders are sometimes provided with small switches for making and breaking the lamp circuit, the switch action being generally controlled by a tap-handle similar to those used for gas-burners. In the Edison holder or socket, fig. 346, the tap carries a cam, which works against the small brass plate, pressing it against the stud on the bottom of the lamp. It releases with a snap action. Socket switches are, however, unsatisfactory, as they easily get out of order, and when high voltages are employed there is some risk of personal injury due to shock. The great defect is in their mechanical design, and the difficulties in the way are considerable. This will perhaps be evident when the smallness of the parts and the comparatively high temperature to which the holder is raised are taken into consideration. Switches are, therefore, more generally independent.

Incandescent lamps can be made to yield any required degree of illumination, from a fraction of a candle-power up to as much as 1000 or even 2000 candle-power, and as the bulb

and filament can be made in almost any shape, it is only natural that there should be a great variety of types designed for correspondingly varied purposes. For ordinary lighting purposes, lamps of 8, 16, 25 or 32 candle-power are the sizes most generally adopted. For lamps of higher candle-power exceptional care has to be taken to ensure sufficiently good electrical connection between the lamp and its holder. The platinum wires passing through the bulb usually terminate in stout wires, connected either to somewhat rigid lugs as illustrated in fig. 348, or, when the lamp is to be subjected to much vibration, in flexible lugs as shown in fig. 349. In large lamps such as those of 500 candle-power, there are frequently a number of filaments, say five, each

FIG. 348

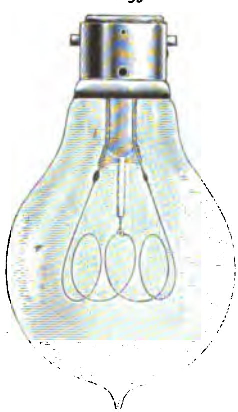
FIG. 349



of 100 candle-power, joined in parallel. In the event of one breaking, the lamp is still of service, and, although its illuminating power is reduced, the electrical power absorbed is reduced in a corresponding degree. The lamps illustrated in figs. 343 and 346 are intended for use on low-voltage circuits, up to, say, 120 volts, but when higher voltages are used, comparatively long filaments have to be employed, and in order that the size of the bulb shall not be unduly increased, the extra length of filament is provided by making additional loops, but it then becomes necessary to 'anchor' the filament to a small glass pillar, as illustrated in fig. 350, otherwise it would be unsafe to place the lamps in a fitting where the filament would incline at an angle of 45° or less

with the horizontal, because of the tendency which would be manifested by the filament to bend over towards the vertical position. Eventually the filament so placed would come into contact with the glass, and break. This tendency is, of course, a maximum where the plane of the filament is horizontal. The increase in the demand for electric lighting has caused the majority of central-station engineers to increase their pressure across the mains feeding the lamps to 200 volts, and in many cases to the full limit allowed, viz. 240 volts. This increase in voltage has the effect of increasing the capacity of the mains, as measured by the number of lamps supplied, but it throws upon the consumer the onus of providing superior insulation and better fittings.

FIG. 350



The 'life' of an incandescent lamp, or the number of hours that it can maintain illumination, varies considerably. Some filaments fracture in a few hours, while others will last for years, and we have seen one which, after burning steadily for at least 8000 hours, was still giving a good light. The vacuum for some reason or other deteriorates more or less in the course of time, while the carbon filament gradually becomes smaller and smaller (increasing correspondingly in resistance), and the glass bulb rapidly diminishes in transparency; and these are points which demand far greater attention than, for example, the substitution of some new material for the platinum leading-in wires. If a comparatively feeble current is employed, the lamp will last much longer than it would with an abnormally powerful one. On the other hand, the luminosity increases much more rapidly than the current strength, so that the question really resolves itself into one of comparative expense. It has been laid down, and is now generally accepted, that the useful life of a lamp is the number of hours taken for its mean horizontal candle-power (M.H.C.P.) to drop 20 per cent. from its standard value when run under standard conditions. Lamps

manufactured by the better makers are designed for a useful life of 400 or 800 hours, the longer life—that is to say, the saving in the cost of lamps, being obtained as the result of a higher cost for current. In other words, a long-life lamp is obtained at the expense of efficiency. It will thus be seen that the life of a lamp cannot well be separated from the consideration of its efficiency.

The efficiency of a lamp is generally described as being proportional to the watts per candle-power—that is to say, to the ratio of the power absorbed to the light emitted—but it might be more correctly referred to as the ratio of the light emitted to the power absorbed—that is to say,

$$\text{Efficiency} = \text{candle-power per watt} = \frac{\text{candle-power yielded}}{\text{watts absorbed}}.$$

The lamps in general use absorb when run on a circuit of specified voltage about 3·5 watts per candle-power, so that the efficiency would be represented by $\frac{1}{3\cdot5} = 0\cdot2857$, but after it has been running for a time there is frequently a decided falling off in the efficiency, and it is a good lamp which absorbs then only $3\frac{3}{4}$ watts per candle, or which has an efficiency $\frac{1}{3\cdot75} = 0\cdot266$. As it has become the general practice to estimate efficiency by the power absorbed per candle-power, no good purpose would be served by adopting the more scientific method, and we cannot do better than repeat that the efficiency of a lamp is measured by the number of watts per candle-power absorbed by the lamp. The efficiency of the lamp is a most important point in determining the economy of this method of lighting, for although the dynamo losses may be small, the losses in the lamp are relatively very considerable. For example, it is a poor dynamo which has a lower efficiency than 90 per cent.; on the other hand, the efficiency of even a good make of incandescent lamp will often range from 3 to 4 watts per candle-power, or, in other words, the 4-watt lamps will be 33·3 per cent. less efficient than the 3-watt lamps.

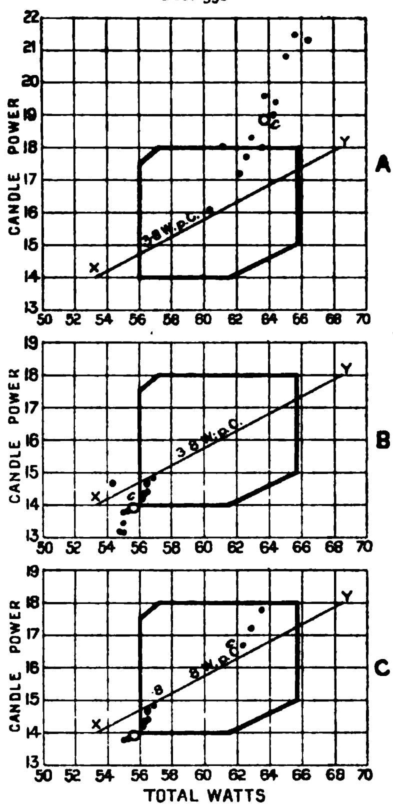
So serious has this question become, more particularly since the controlling patents lapsed and the market became flooded with very cheap and very inefficient lamps, that the Engineering

Standards Committee has taken the matter in hand, with a view to formulating a series of tests and conditions which, if generally adopted, will materially improve the character of the lamps supplied. It is recommended that for testing purposes 5 per cent of the lamps concerned (with a minimum of 20 lamps) should be selected and the whole 'parcel' or quantity accepted or rejected according to the proportions which pass an exhaustive series of tests, both mechanical and electrical. One of the tests is for 'spotted' or unequal filaments, and is made by subjecting it to a pressure of approximately 40 per cent. of its standard voltage. This will suffice to show up the weak places in the filament, as such places will be appreciably more heated than the rest of the filament. It is also stipulated that the insulation resistance between the cap and the filament shall be not less than 1000 Ω. A table of the ratings and limits of lamps of various sizes and voltages has been compiled by the Committee and is very interesting. Thus a 16 candle-power 110-volt 400-hour lamp is defined as one which should have as its standard rating a M.H.C.P. of 16 with an efficiency of 3·1 watts per candle, or a total of 49·6 watts, but that the acceptable limits of individual lamps should be 14 to 18 candle-power at 45·6 to 53·7 watts, while the average limits of the lamps under tests should be from 14·7 to 17·3 candle-power at 47·1 to 52·1 watts. The watts per M.H.C.P. should be between 2·6 and 3·6, the corresponding wattage for a useful life of 800 hours being 3·0 to 4·0. Taking a 16 candle-power 400-hour lamp on a 220-volt circuit, the standard rating is 3·7 watts per M.H.C.P., with a total of 59·2 watts. The acceptable limits for individual lamps are 14 to 18 candle-power with a consumption ranging from 54·5 to 63·9 watts, while the average limits should be from 14·75 to 17·25 candle-power with a consumption ranging from 56·3 to 62·1 watts. The watts per M.H.C.P. should be between 3·1 and 4·3, the corresponding efficiency for 800-hour lamps being 3·5 to 4·7 watts per M.H.C.P.

It will be seen that the limits if viewed on a percentage basis allow a very wide margin, and there is no doubt that even on this basis a very large proportion of the lamps at present supplied would fail to comply with the requirements, and it will be at once evident that the cheap lamp is commercially dear.

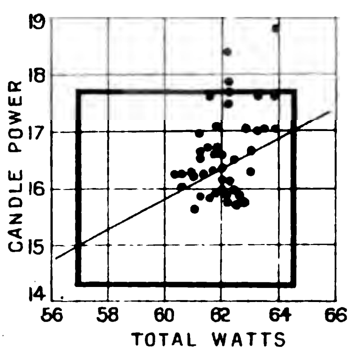
Mr C. C. Paterson, in a paper read before the Institution of Electrical Engineers in January 1907, described a most instructive series of tests, undertaken at the National Physical Laboratory, and a few of the results will doubtless be of interest to the student. He points out that the electrical tests specified by the Engineering Standards Committee may be divided into two classes, viz. (*a*) Tests to determine the initial rating of the lamps and their uniformity in candle-power and efficiency, and (*b*) tests to determine the maintenance of the candle-power during the life of the lamp. In carrying out the tests for initial rating, parcels of lamps were obtained from ten British makers. The lamps were of the ordinary 200-volt 16 candle-power type, and each set or parcel comprised twelve lamps. The results for these sets of lamps are illustrated in the 'Target' diagrams, fig. 351. The lamps were tested for M.H.C.P. and total watts at the voltage marked on the lamps, the results for each lamp being indicated by a dot. All the dots which fall within the six-sided figure in each of the diagrams represent lamps which fall within the limits of the Standards Committee's specification for 3·8 watt lamps. The oblique lines X Y represent the relation which should subsist between candle-power and watts to comply with the actual

FIG. 351



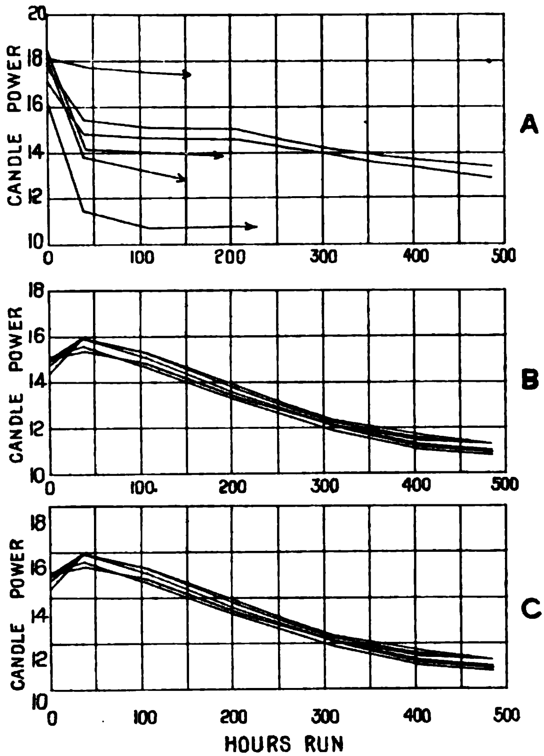
standard of 3·8 watts per M.H.C.P., while the small circles *c* indicate the average for the batch of lamps included in each diagram. The disparities of the results are instructive. In the first batch (A) the range of candle-power is considerable and the average efficiency is high, pointing to a short useful life. In the batch B the average efficiency is low, only one lamp being above the standard, but the range is very short, and an even but expensive un might be predicted. In the batch C the lamps all fall within the standard limits, but they cover a fair range as to both candle-power and watts, and they have just a shade over the standard efficiency. Taking the whole of the lamps tested into consideration, the M.H.C.P. ranged from 11·0 to 21·5, while the efficiency ranged from 3·04 to 5·21 watts. A target diagram of 45 American lamps of 200 volts tested by Mr. F. C. Bailey at the New York Electrical Testing Laboratories is given in fig. 352. The uniformity is remarkable and is largely attributable to the superiority of American practice as to supply voltages and the enforcement of a rigid lamp specification. Mr. Paterson points out that if the American voltage limits had been applied to the average of each batch of English lamps which were included in the tests described, about 45 per cent. of them would have failed to meet the requirements, and that, if an average of 16 initial candle-power had been insisted upon, only 35 per cent. would have passed the test. The limits prescribed by the Standards Committee would allow 60 per cent. to pass. The results of some further tests are shown in fig. 353, and refer to a portion of the series of 'life' tests. Six out of each of the ten sets of lamps which were subjected to the initial rating tests were selected, the lamps chosen being those which came nearest the mean. The lamps were mounted on racks, and the voltage on

FIG. 352



each lamp was so adjusted that the initial efficiency was 3·8 watts per M.H.C.P. and the test was continued until the luminosity had fallen to 80 per cent. of the initial value. Fig. 353 shows the results of six of the lamps of each of the batches whose initial ratings are indicated in fig. 351. The short life of the lamps in

FIG. 353



batch A is very noticeable notwithstanding the fact that instead of being run at their normal voltage, the pressure was reduced so as to let the lamps start at 3·8 watts per candle. It will be remembered that the lamps in batch B had a low but uniform efficiency. They would therefore have to be started at more than 200 volts

in order to raise their efficiency to 3·8 candles. Notwithstanding this, the lamps on the life test gave a good account of themselves and the uniformity of the six life curves is remarkable. Concerning batch C it may be observed that the six life curves are symmetrical, but not nearly so close together as in batch B.

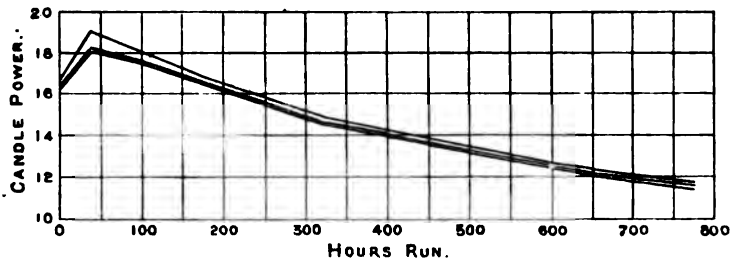
It has been suggested that by subjecting the lamps selected for testing purposes to a considerably higher voltage, say 40 per cent., than the normal, the much shorter time which would elapse in reducing the candle-power to 80 per cent. of its initial value would be a fair guide as to the performance of the lamps at the normal voltage, and would therefore enable a life test of correspondingly shorter duration to be made. Unfortunately Mr. Paterson's trials have not confirmed this view, for he finds that after running a number of lamps for one hour at an increase of 40 per cent. in the voltage, the reduction in candle-power bore no definite relationship to the percentage fall of other lamps taken from the same parcels when run at their normal voltage for 1000 hours. In fact, not only did one make or parcel differ from another, but individual lamps from the same parcel also differed very materially.

A number of lamps of various candle-powers made by the British Thomson-Houston Company have recently been tested at the National Laboratory, and, although we cannot reproduce all the tests, it is a very noticeable feature that they show a wonderful uniformity in initial rating and in durability. Concerning the 16-candle-power lamps, the actual average M.H.C.P. and the efficiency which was guaranteed at 3·9 watts worked out at 3·81. Fig. 354 illustrates the result of the life test on three of the 16-candle-power lamps.

A series of tests made independently by a very large consumer gave some very striking results, but we will confine ourselves to two of them, with the object of showing the difference in the behaviour of good and bad lamps. Fig. 355 refers to a test of six 8-candle-power 105-volt lamps. Not only is their behaviour uniform, but the efficiency is well maintained. One lamp gave out after about 770 hours, and another after nearly 1600 hours' run, but none of them fell below about 80 per cent. of their nominal candle-power during the 1700 hours covered by the

diagram. It will also be observed that the reduction in efficiency was very slow. Now let this diagram be compared with that given in fig. 356, which represents the results of the tests of three 16-candle-power 105-volt lamps by another maker. In the 1700 hours' run the lamps had lost more than 50 per cent. in

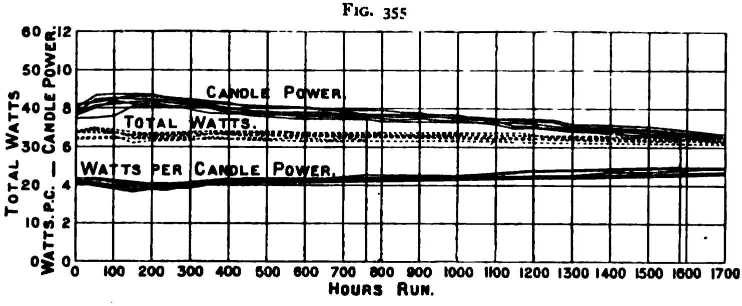
FIG. 354



candle-power, while the efficiency had fallen to about half the initial efficiency.

The fall in efficiency generally observable is attributable to the gradual disintegration of the filament, and this defect is more

FIG. 355

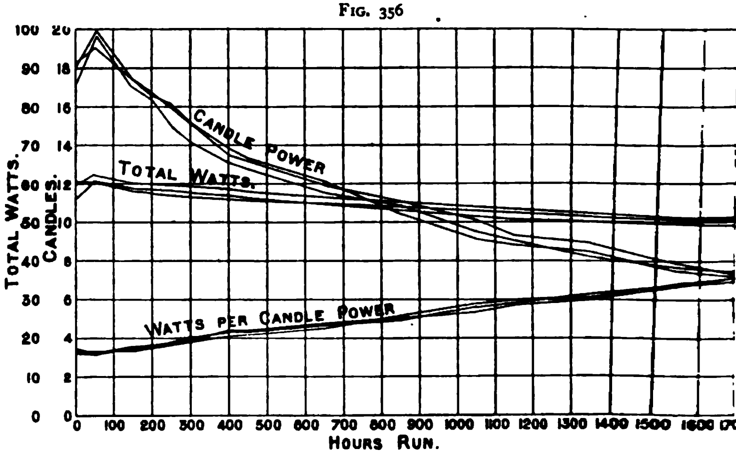


particularly noticeable with high efficiency lamps. It should be evident that very fine filaments are less durable than the more substantial ones, and it is therefore undesirable to push the incandescence too far—that is to say, to run the lamps at a high luminosity. When this is done the saving in current

may be more than counterbalanced by the destruction of the lamps.

The reduced transparency of the bulb, which arises from a deposit of the disintegrated carbon upon the inner surface of the glass, increases with age, but it will obviously vary inversely as the area of the inner surface of the bulb, for if we double that area, a given number of particles falling upon it will be only half as dense. The deposit on the glass not only reduces the transparency of the bulb, but it also involves a reduced section of the filament, the resistance of which is thereby increased.

FIG. 356



Such an increase in resistance means a feebler current and a feebler state of incandescence. We thus see that less light is emitted by the carbon, and that of this light a larger proportion is absorbed by the blackened bulb than would be the case with a clean one. The smaller current passing through the filament would, under ordinary circumstances, give a proportionally smaller reading at the meter, but sometimes the current taken by an old lamp is actually larger than that taken by a new one, due probably to a fine deposit of carbon near the neck of the lamp; this deposit provides a second or high resistance shunt circuit for the passage of the current from platinum to platinum.

It is a very interesting feature that the deposit is not uniform, but is usually of greater density in the vicinity of the filament, as though the particles were repelled in straight lines from the filament on to the glass. It has been observed that lamps made with filaments which have been carbonised at a comparatively low temperature blacken very readily, whilst when made with others which have been raised to a very high temperature they resist the tendency very much more effectually. This is probably due to the fact that the filament carbonised at a high temperature is purer and more dense than those which have not been heated so intensely. Similar results have also been observed to occur in lamps when low or high temperature flashing has been employed. These facts tend to prove that the blackening is due to a partial volatilisation and recondensation of the carbon particles. Certainly the temperature of the incandescent filament—about 2000° C.—is much lower than that already ascribed to the positive carbon in the arc; but this discrepancy may to some extent be very plausibly accounted for by the fact that in the incandescent lamp there is practically no air pressure, and that this absence of pressure may lower the temperature of volatilisation, just as an increased air pressure on the arc so alters the condition of affairs that a higher E.M.F. becomes necessary in order to maintain the arc consequent upon the increased temperature of volatilisation. If this be the true explanation of the blackening phenomenon, it follows that the difference in degree between the filaments prepared at low and high temperatures respectively must arise solely from the circumstance that a comparatively loose condition of the carbon is especially favourable to the formation of carbon vapour. On the other hand, we can conceive that the readiness with which a filament could be disintegrated would vary inversely as its density. The film, by whatever process it may be formed, is apparently pure carbon, as it is a sufficiently good conductor to take a continuous coating of copper when placed in an electrolytic bath.

If the blackening of the bulb were due to the simple breaking away of the carbon particles, then we might imagine that the durability of the lamp would be materially less on an alternating than on a direct-current circuit, because of the constantly varying

conditions to which the filament would be subjected, but the tests which have been made tend to show that a lamp on an alternating circuit is as efficient and durable as when placed on a direct-current circuit.

To show the effect of the carbon film, an experiment is recorded in which an old filament was removed from its bulb and transferred to a new one, when the light emitted and measured under similar conditions showed an increase of 15 per cent. In this case, however, the degree of exhaustion may have been, and probably was, different, and it is difficult to guarantee absolutely uniform transparency in a number of bulbs, so that the importance of a test of this kind might easily be over-estimated.

Reference was made in the early pages of this chapter to the use of metal filaments for incandescent lamps, and it will be remembered that the chief difficulty was the comparatively low fusing point of platinum, the most obdurate of the metals obtainable in a practical form until within the last few years. Latterly, however, quite a number of the lesser known metals have been obtained in sufficient quantity to justify further experiments, and these have demonstrated that the requisite temperature can be maintained without melting or disintegrating, and that in the vacuum which can be provided, the metal is not consumed by chemical combination. The great difficulties arise from (*a*) the relatively high conductivity of the metals as compared with carbon, and (*b*) the problem of manufacturing the wire or filament. The second difficulty is one which we can hardly enlarge upon here, but in regard to the first it may be pointed out that the high conductivity, or, shall we say, the relatively low resistance, of the metal involves the use of an exceptionally fine filament, although even then the length exceeds considerably that of a corresponding carbon filament. As a matter of fact, metal-filament lamps, of which there are now several kinds, cannot on this account be made for circuits of more than 125 volts or thereabouts, and even then the filament has to be something like 2 feet in length. In consequence of the relatively large radiating surface thus provided, the luminosity of the lamp is considerably higher than with a corresponding carbon filament. Thus at the

time of writing the smallest metal-filament lamp yields a light of about 25 candle-power, although with a little more research and careful manufacture there is reason to suppose that smaller lamps, or rather lamps with smaller or shorter filaments, will be brought within the range of practicability. An important advantage is derived from the greater proportional surface area and from the fact that that surface is smooth and bright, viz. that the proportion of the energy expended upon the lamp which is radiated in the form of luminous rays is greater with the metal than with the carbon filament. As a result the metal-filament lamp is capable of running commercially at an efficiency of 2 watts or less per candle-power as compared with 3·5 to 4 watts for carbon-filament lamps. Some manufacturers even go so far as to claim an efficiency of 1 watt per candle-power. The metals which so far have proved most satisfactory are osmium, tantalum, and tungsten. Dr. W. von Bolton, in a paper read before the Elektrotechnischer Verein of Berlin, details some very interesting experiments with metals such as vanadium, niobium, and tantalum, and the most promising for the object in view was tantalum. It will doubtless be readily imagined that so long as a particular substance remains exceedingly rare, and extremely difficult to produce in a state of actual purity, its attributes are but imperfectly known, and this has proved to be the case with tantalum and other similar metals; but in consequence of the urgency of the problem involved in finding a better material than carbon, the real properties of the rarer metals have been minutely investigated and have shown themselves in very different colours from those previously assigned. Dr. von Bolton observes that tantalum when cold is assailable by hydrofluoric acid only, and describes many other features in connection with its chemical properties. It is a metal which can be rolled or drawn, and it has, prior to the passage of a lighting current through it, a tensile strength which is something like 18 per cent. higher than that of mild steel. It has a coefficient of expansion between 0° C. and 60° C. of 0·0000079, and fusion is preceded by a gradual softening, which extends over a very considerable range of temperature. Its specific resistance has been estimated on different occasions, but with various results, due possibly to the gradually increasing purity of the samples under

test. The most recent result is 0·165 for a wire 1 metre long and 1 square millimetre cross-section. When placed in a lamp and run at an efficiency of 1·5 watt per candle the resistance of such a wire rises to about 0·83 ohm.

It is a noteworthy feature that while metal-filament lamps are in some cases, more particularly with the higher candle-power filaments, run satisfactorily on alternating current circuits, their general use for such purposes cannot be recommended, owing probably to their inability under such conditions to withstand the mechanical strains to which they would be subjected.

FIG. 357

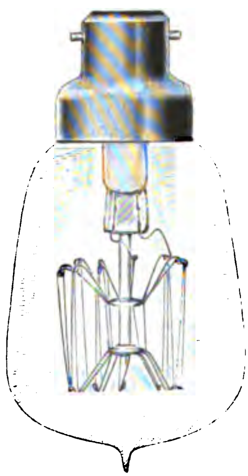


Fig. 357 illustrates the present form of tantalum lamp, designed for a pressure of 110 volts and with an illuminating value of 25 Hefner candle-power. (The Hefner is the German standard of light, and is referred to later in this chapter.) The efficiency is said to be 1·5—that is to say, it consumes 1·5 watt per Hefner candle-power. The weight of the filament is 0·022 gramme, its length is 650 millimetres, and its diameter is 0·05 millimetre. In order to suitably dispose or arrange so long a filament in a bulb of about the same dimensions as a corresponding carbon-filament lamp, the lamp contains a short pillar of glass, at each end of which is a small disc, into which are cast or moulded a number of small copper wires bent outwards like the ribs of an umbrella. The wires are all insulated from one another. The lower disc carries 11 of these wire arms, and the upper disc 12. The ends of the arms are bent into small hooks, and the tantalum wire is threaded over them, the additional arm on the upper disc being provided to support the end of the wire, the two extremities of which are continued by short lengths of platinum to the glass stem connecting the pillar above referred to to the neck of the lamp. As most lighting circuits are provided with a pressure exceeding 200 volts, two tantalum lamps must in

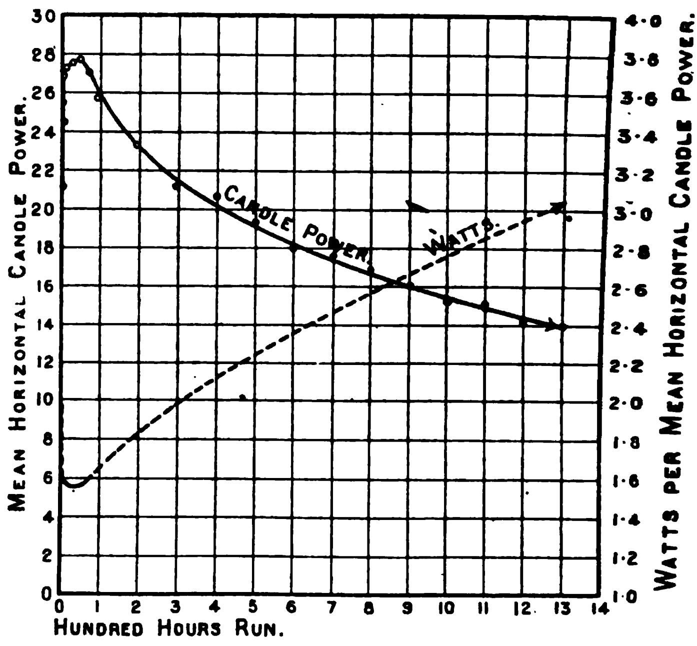
such cases be joined in series. This can be done by procuring a two-light ball fitting or something similar, and connecting it to an 'adapter,' by means of which the two lamps can be supported in an ordinary holder (fig. 344) provided for, say, a 16-candle-power carbon lamp; or the installation may be specially wired for running two lamps in series. The light emitted is much whiter than that usually associated with carbon lamps, and is very effective, but if the lamp is placed in any other than a vertical plane it will be noticed that the current causes the filament to elongate sufficiently to make a perceptible sag in the wire. Sometimes the filament will break under vibration, and if the broken end falls across another length, the passage of the current will fuse the two together. The shortened circuit through the lamp results, of course, in the passage of a heavier current accompanied by a higher efficiency, which involves a correspondingly shortened life.

In common with all other pure metals there is an appreciable increase in resistance as the temperature of the filament rises, and, as a consequence, a lamp which is overrun, or to which an excessive voltage is applied, does not suffer such a large increase in the strength of the current as is the case with carbon-filament lamps. In other words, an increase in voltage means an increase in resistance, and a correspondingly smaller increase in the current; and, *vice versa*, a fall in voltage is accompanied by a fall in resistance and a correspondingly smaller fall in the current, so that a metal-filament lamp gives on an ordinary lighting circuit, where a small variation of the voltage up or down is usually permitted, a more uniform illumination than does a carbon-filament lamp.

A number of tantalum lamps have been subjected to an exhaustive series of trials at the National Physical Laboratory and with very interesting and instructive results. Fig. 358 illustrates the results of an efficiency test of one of the lamps. The tests were prolonged for 1300 hours, during which the candle-power, starting at 27, rose rapidly to nearly 28 at the end of about 50 hours' run (the maximum is usually reached after 25 hours' run, the initial increase being ascribed to a change in the physical structure of the filament). The illumination then began to fall,

and at the end of 400 hours' run had fallen to about 20 candle-power—that is to say, to about 80 per cent. of its standard (25 candle-power) rating. But even then its efficiency was only 2·1 watts per candle—that is to say, the current would cost about one half as much as a carbon lamp for a similar illumination. At the end of its 1300 hours' run it was still more efficient than a really

FIG. 358



good carbon lamp at the beginning of its 'life.' Fig. 359 is also instructive. It represents the average conditions of a number of lamps which were subjected to a test of 1000 hours' run. In this figure the candle-powers are plotted vertically, and the watts per candle horizontally. The candle-power and efficiency of each lamp (measured after a 20 hours' run) may therefore be plotted in the diagram and represented by a dot somewhere in the figure.

The rectangle near the upper left-hand corner of the diagram represents certain limits of candle-power and efficiency, viz. between

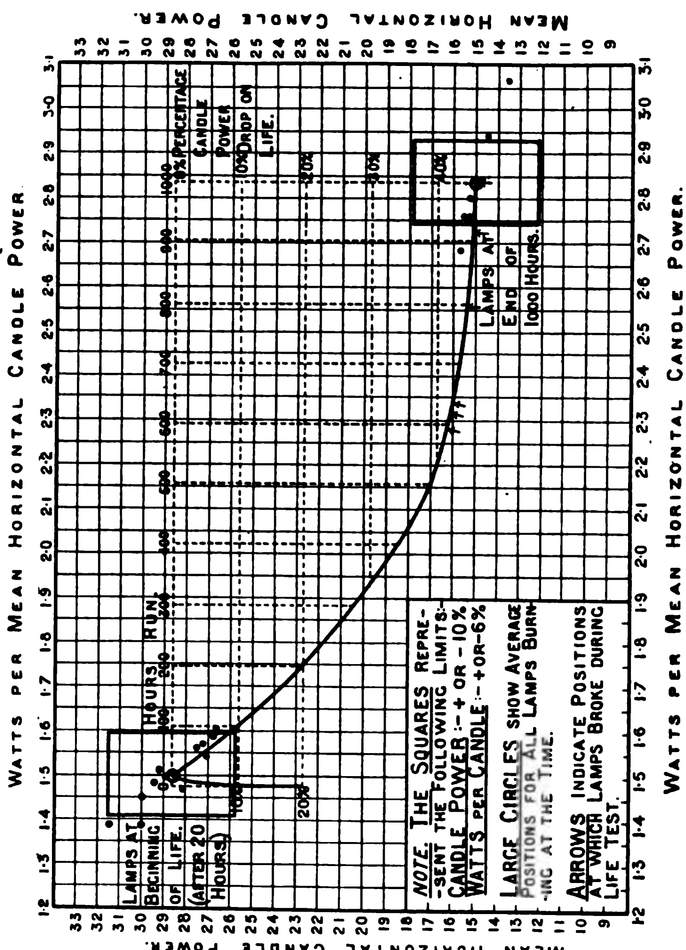
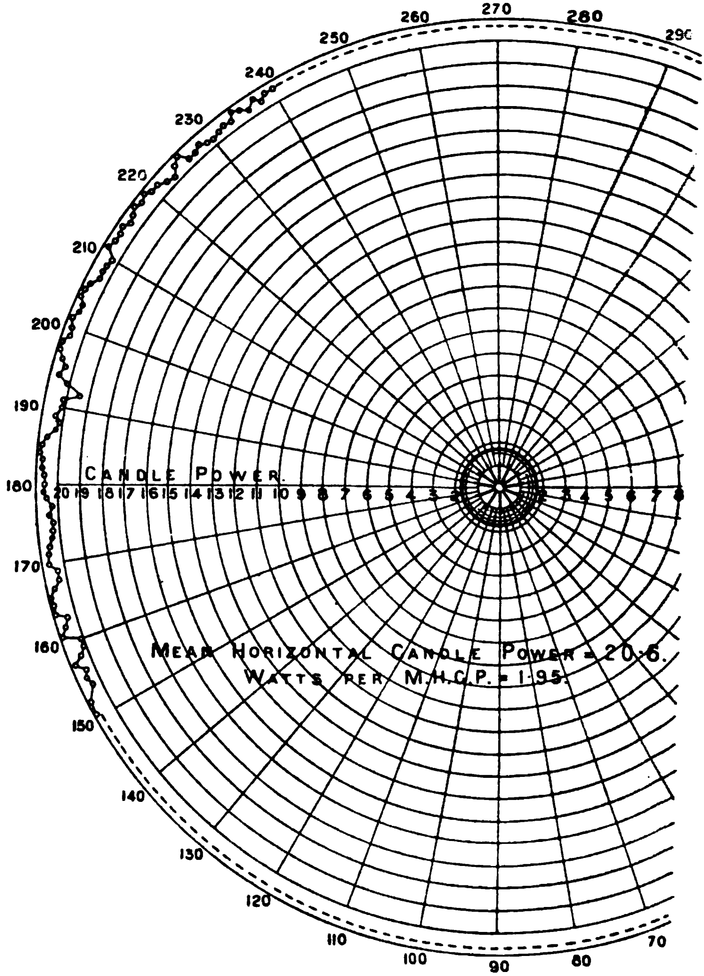


FIG. 359

+ or – 10 per cent. in candle-power and + or – 6 per cent. in watts per candle, so that all lamps which fall within these limits

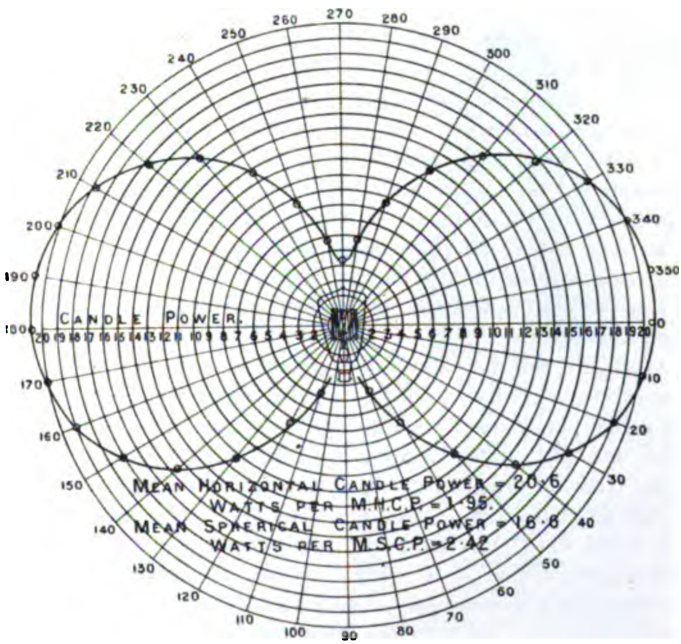
will be represented by corresponding dots within the rectangle. These are the positions when both candle-power and efficiency are about a maximum, and the centre of gravity of all these

FIG. 360



positions is taken as the datum point of the diagram. The rectangle near the lower right-hand corner embraces dots representing the lamps which at the end of 1000 hours fell within the above limits of the average, the circle indicating the average for all the lamps which were still burning at the end of the run.

FIG. 361



Figs. 360 and 361 illustrate in a very telling manner the illuminating power of the lamps in planes respectively at right angles and parallel with the axis of the lamp. The uniformity of the illumination is very noticeable and to some extent arises from the fact that the filament is essentially a 'tube' instead of a simple loop, so that the unusual length of the filament is not altogether devoid of advantages. The tests were taken after the lamps had been running for about 110 hours in order to allow

the lamps to have attained a more constant value than in the earlier portion of the run.

These results (for which we are indebted to Messrs. Siemens) speak well for the prospects of metal-filament lamps, but the tests above referred to were taken in 1905 and already there have been chronicled several improvements, so that in the near future there is every prospect that further advances will be made, and the metal-filament lamp be recognised as the electrical engineer's response to the latest form of the incandescent-gas mantle.

The Nernst lamp, named after its inventor, constitutes a class by itself. It is a lamp of which much was expected, but has not been adopted so freely as was anticipated. It consists essentially of a short and comparatively thick rod composed mainly of zirconium oxide. All oxides, it may be remembered, are insulators at ordinary temperatures, but fall in resistance as the temperature rises. The rod is therefore raised by external means to a fairly high temperature, until, in fact, it attains such a temperature that its resistance is sufficiently reduced to enable it to transmit the required current.

Owing to the fact that the illuminating rod does not suffer combustion in contact with the air, the lamp has the advantage that it does not require a vacuum, and consequently when from any cause one part of the lamp is injured or destroyed, that part can be renewed without necessarily sacrificing the remainder.

Fig. 362 illustrates one of the several types of Nernst lamp. The spiral which can be seen inside the globe consists of a platinum wire coiled on to a small rod of porcelain or other suitable material, and then covered with a small quantity of the same material. This spiral envelops the illuminating rod. In the cap of the lamp is a small electro-magnet, with a flexible or hinged armature. There are two circuits through the lamp. Starting from the positive terminal the path of one of these circuits is along the armature to a contact stud, and thence to the heating spiral and away to the negative terminal. The other path or circuit is from the positive terminal to the magnetising coil of the electro-magnet, and thence through a resistance coil of iron wire, also contained in the cap, to the illuminating rod. When the current is switched on, the resistance of the rod is too great to

allow any current to pass through its circuit, and the electromagnet is therefore unaffected; the circuit through the platinum wire is, however, complete, and the current passing through the wire makes it red hot and thereby heats the illuminating rod. As the temperature of the rod rises, and its resistance falls, the current through the magnetising coil rises until the core is sufficiently magnetised to enable it to attract the armature and break the circuit through the platinum wire. The whole current then passes through the rod, and its resistance falls so rapidly that an excessive current would in the absence of the iron-wire resistance soon be permitted to pass. The iron resistance, however, rises rapidly in temperature, and consequently in resistance, and this rise in resistance is adjusted so as to compensate for the fall in the rod, and the current is thereby kept within the desired limits. It is an interesting feature that the iron resistance is confined in an atmosphere of nitrogen, in order to prevent the rapid oxidation which would ensue were ordinary air in its vicinity.

FIG. 362

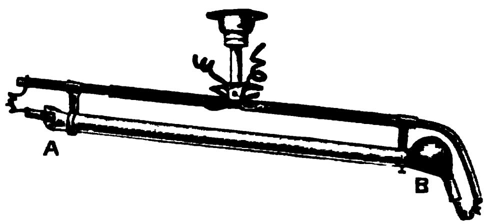
Lamps are constructed for pressures ranging from 100 to 260 volts, but are more satisfactory at the higher voltages. The luminosity ranges from 14 to 850 candle-power, and the efficiency is very high, viz. about 1·5 watt per candle-power.

For some of the lamps an efficiency of 0·9 watt per candle-power is claimed. The light when the lamp has attained its normal temperature, which it does in a remarkably short space

of time, is steady, and owing in some degree to the density of the globe the illumination is agreeably diffused.

There is another type of lamp which has of late years shown some development, but which it is somewhat difficult to classify. It consists of a glass tube containing a very small amount of mercury vapour through which the current passes. It is known as the Cooper-Hewitt mercury vapour lamp, and its construction is illustrated in fig. 363. A B is a sealed glass tube about one inch in diameter with an enlarged bulb, B, at one end containing a quantity of mercury which is connected, by means of a platinum wire fused through the glass, with the negative pole of the generator, the positive pole being connected by means of another piece of platinum wire fused through the end A and terminated in a cup-shaped sheet-iron electrode. The glass tube is exhausted of air,

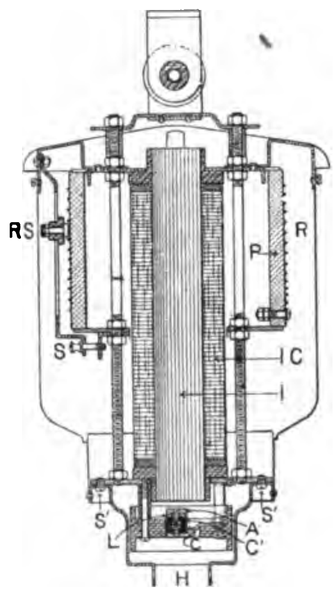
Fig. 363



so that except for the mercury a good vacuum is obtained. Connected to the negative end is a resistance coil, the function of which is to prevent an excessive current passing through the tube. When the lamp is in the position shown there is practically no vapour in the tube, and the resistance between the two ends A and B is therefore far and away too high for any current to flow. In order to start the current the tube has to be gently tilted until a fine thread of mercury passes from B to A. This permits a current to flow which volatilises a small portion of the mercury, so that when the tube is returned to the horizontal or thereabouts there is sufficient mercury vapour to permit the continuance of a current under ordinary voltages. The mercury vapour then becomes incandescent, and a soft, steady, and not very disagreeable light results, although there is a total absence of red rays and a great

predominance of green. Owing to the length of the tube, which ranges from a little over two feet to about four and a half feet, the light is not dazzling, but is well diffused. The normal current is 3·5 amperes, the difference in length being dependent upon the voltage, the maximum pressure being about 120 volts. For circuits of higher voltage two or more lamps are placed in series, with automatic regulators and shunts for each lamp, so that the failure of one lamp should not prejudice any other in series with it. The efficiency is said to be as low as 0·5 watt per candle-power. When the current is switched off the mercury re-liquefies and returns to the reservoir or 'condensing chamber.' Of course the tube is supported by a rod and other gear, as indicated in fig. 363, so that it may be suitably suspended from a ceiling. In the simpler types a light chain or cord is provided for tilting and restoring the tube. In the automatic type the current does the tilting by means of a solenoid which acts on a soft-iron plunger linked to the lamp-holder. With a lamp of the type shown in fig. 363 the resistance coil is separate and is fixed in any convenient position, but with lamps designed for series working the resistance is contained in what may be called the lamp-holder. Fig. 364 shows a cross-section of this holder. It contains a laminated iron core, I, over which is wound an inductance coil, IC. P is a porcelain cylinder, over which is wound the resistance coil, R. The amount of the resistance in circuit is adjustable by means of the sliding contact, RS. The contact is carried on a strip which can be fixed in position by means of the screw S. At the bottom of the holder is a carbon shunt, consisting of two

FIG. 364



blocks of carbon, of which one block, C, is fixed, the other, c^1, being movable, and controlled by a hinged lever, L. This lever also carries a soft-iron armature, A, which is controlled by the core I. s^1 s^1 are screws by means of which the carbon shunt can be exposed for inspection, while H is the collar into which the lower portion of the lamp, that is to say, the rod and tube can be fixed.

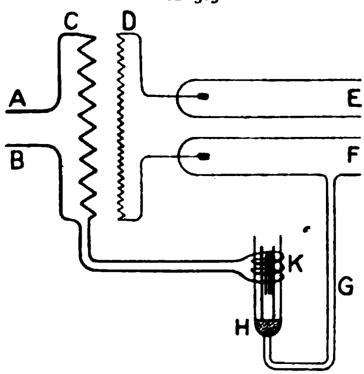
The particular portion of the surface of the mercury at which the current enters is called the disintegrating point, but this point travels to and fro over the surface of the mercury. It is at a high temperature, and it is therefore necessary that the mercury should cover the end of the platinum leading-in wire, otherwise the air occluded in the platinum will be driven out under the high temperature and impair the vacuum which is essential to the proper working of the lamp. The resistance coil, R, acts very much in the same way as the steadying resistance provided with an arc lamp and enables the current to be adjusted to the required value. The function of the inductive resistance, *i.e.* the inductance coil IC, is to assist in maintaining a uniform current by setting up variations in opposition to those due to the variations of the resistance of the disintegrating point on the surface of the mercury.

It is important that the current should not fall below 3·5 amperes nor rise above 3·8, and that it should pass through the tube in the proper direction, otherwise a portion near the positive end will be dark, and the light will flicker badly, the lamp being ultimately 'burnt out.' In this eventuality the tube will be blackened like an old carbon-filament lamp, and will also be spotted with mercury.

Another very interesting type of lamp, known as the Moore vacuum tube, is illustrated in fig. 365. It is a development of the well-known Geissler vacuum tube, and, like the mercury vapour lamp, there is some doubt as to whether it should be classed as an arc or an incandescent lamp. Essentially, it consists of a long tube containing a rarefied gas through which a high-voltage discharge is maintained, so that the illumination results from the rapid vibration imparted to the gaseous particles in the tube. To those who have the opportunity, the 'lamp' may be seen

illuminating the courtyard in front of the Savoy Hotel in London, but it is understood that there are several similar installations in the United States. E F represent the ends of the sealed glass tube which extends round the room or other place to be lighted, and may be as much as 200 feet in length, its diameter being about 1·75 inch. It is supported at suitable intervals by brass rings, and is supplied with gas according to the colour of the light required, air, for example, giving a pink light, and nitrogen a yellow illumination. Naturally, a high potential discharge is required, and this, amounting to from about 2000 to 12,000 volts, is obtained by means of a transformer, the primary coil (C) of which is supplied with an alternating current at ordinary pressures, say 220 volts, by way of the leads A B. The terminals of the secondary coil, D, are joined direct to the ends of the tube E F, the electrodes inside the tube being of carbon. The service supply is carried through the usual switch and fuses to the transformer, and the whole of the high-voltage apparatus, except the illuminating tube itself, is confined in a steel box. The remarkable feature is that the contained gas diminishes in quantity as the life of the 'lamp' progresses, and this diminution is accompanied by the deposition of minute quantities of dust as though the gas gradually solidified under the influence of the discharge, whence the resistance of the remaining gas rises, and the current consequently falls. Whether that be the true explanation or not it is found necessary to supplement the quantity of gas from time to time, and the feature of the Moore system is the means for automatically accomplishing this object. A feeder tube, G, is fused into one side, F, of the illuminating tube. The free end of the tube G is contracted and enters a carbon plug, H, which, while it is impervious to mercury, will allow gases to be drawn through

FIG 365



owing to the high vacuum of the lighting tube. This carbon plug is normally covered with a thin layer of mercury. Partly immersed in the mercury and concentric with the carbon plug is another smaller and movable glass tube, the upper end of which is fitted with soft-iron wire which acts as the core of a small solenoid, K, connected in series with the primary coil, C, of the transformer. The action of the solenoid is to lift the concentric glass tube partly out of the mercury, the surface of which falls, and thereby causes a minute conical tip on the carbon plug to be exposed, and allows an extremely small quantity of air or other gas to filter through it and find its way through G into the tube F. In normal conditions the carbon tip is exposed for about one second every minute.

The student will, perhaps, remember that the current through the primary coil of a transformer varies with the output of the secondary coil, and the solenoid controlling the feeding valve of the Moore lamp is so adjusted that when the resistance of the gas is approaching its minimum, *i.e.* when the current through it is approaching its maximum, the current through the solenoid shall be just strong enough to raise the concentric glass tube and allow the gas to pass through. The passage of this gas increases the resistance of the tube E F, and the current in the solenoid therefore falls, and allows the glass tube to drop and seal the carbon tip with mercury. The efficiency of the lamp is largely dependent upon the gas which is used in the tube: it is claimed that with nitrogen it has an efficiency of 1·3 watt per hefner, but this ignores the losses in the transformer chamber, which should be included in order to make the lamp comparable with other types which are supplied direct from the mains.

When filament lamps are being run on a constant potential circuit—that is, when they are joined across the mains in parallel—their resistances, if they are all of the same candle-power and efficiency, must be uniform, so that they will take the same current strength; but if lamps of different candle-power are to be employed on such a circuit, then their resistances must vary inversely as the currents they are to carry—that is to say, inversely as their required candle-power. For example, an 8-candle-power lamp should require only half the expenditure of electrical energy that

should be necessary with a 16-candle-power lamp. Now the electrical power expended in a lamp (or the number of watts) is proportional to the potential difference multiplied by the current strength. If, therefore, we represent the electrical power in watts by W, the pressure in volts by E, and the current in amperes by C, then $W = E\,C$. But E is constant; therefore if W for a 16-candle-power lamp is twice as much as for an 8-candle-power lamp, R in the former case must be half as much as in the latter. Let us suppose that we have a 100-volt circuit, and that a 16-candle-power carbon-filament lamp takes 60 watts, also that an 8-candle-power lamp takes 30 watts, then for the former

$$\begin{aligned} W &= E\,C \\ &= 100 \times 0{\cdot}6 = 60, \end{aligned}$$

and for the smaller lamp

$$\begin{aligned} W &= E\,C \\ &= 100 \times 0{\cdot}3 = 30. \end{aligned}$$

But by Ohm's law, $R = \frac{E}{C}$, and for the 16-candle-power lamp

$$R = \frac{E}{C} = \frac{100}{0{\cdot}6} = 166 \text{ ohms.}$$

Similarly for the 8-candle-power lamp

$$R = \frac{E}{C} = \frac{100}{0{\cdot}3} = 333 \text{ ohms.}$$

The obvious meaning of this is that, for a given voltage and for a given make and length of filament, the higher the illuminating power which a lamp is required to yield the thicker must the filament be. If the filament suitable for a 16-candle-power lamp on a circuit of given voltage were halved, and the halves placed in separate bulbs, each would give a luminosity of approximately 8 candle-power, providing that the two lamps were placed in series. If one of them were joined direct across the mains, the current that would flow through it would be twice the normal strength, and the filament, being raised beyond the temperature

of volatilisation, would break. The resistance of carbon falls somewhat rapidly with an increase of temperature, so that the resistance of a 16-candle-power 100-volt lamp is more than 300 ohms when cold, or about twice as high as when it is hot.

When we have once established a fair average efficiency it becomes a very simple matter to estimate the amount of light obtainable from a given electrical power, or, conversely, the power that would be required to maintain a given number of lamps. On the basis of $3\frac{3}{4}$ watts per candle, a 16-candle-power lamp taking 60 watts would on a 60-volt circuit require a current of 1 ampere, and on a 100-volt circuit 0·6 ampere.

If we have an available potential difference of 100 volts and a current of 60 amperes, we have a total power of 6000 watts, which—ignoring, for the time being, the resistance of the mains—would suffice to maintain a hundred 16-candle-power lamps, or fifty 32-candle-power lamps. Or if we require to light two hundred 16-candle-power lamps at 100 volts, then we must provide a current of 120 amperes. It is almost unnecessary to repeat that every lamp is made to run at a given or definite voltage, and that it would be quite impracticable to place the same lamp indifferently on a 50 and on a 100 volt circuit. The voltage that the lamp will require is determined by the dimensions of the filament, and every filament is so dimensioned as to yield its standard luminosity at the highest temperature compatible with durability, and any material increase upon that temperature would tend to cause volatilisation or disintegration and consequent rupture of the filament.

A 16-candle-power carbon-filament lamp, when run at 4 per cent. below its normal voltage, suffers a loss in luminosity of 20 per cent., while an excess pressure of 4 per cent. results in an increase of 25 per cent. in luminosity, so that the luminosity varies much faster than the volts, and when the illumination is reduced to about one-half of its normal amount, the power absorbed in the filament is reduced by only 20 per cent. or thereabouts. In one series of tests it has been shown that an increase of 10 per cent. in the voltage results in an increase of 12 per cent. in the current, which causes an increase of 80 per cent. in the candle-power and reduces the life of the lamp to

one-fourth of its normal. For reasons already explained the variations with metallic-filament lamps are appreciably less than with carbon filaments.

It is, therefore, a false idea of economy to imagine that by under-running an advantage will be gained. A reduction of only 2 volts makes itself very apparent in the amount of light emitted by the filament, and although it will probably result in a prolongation of the life of the lamp, the advantage thus accruing is more than neutralised by the reduced efficiency. Although there is a considerable saving involved in the prime cost of mains and conductors by using high-voltage lamps, there is a limit to which this saving can be advantageously carried. An 8-candle-power lamp, for instance, when constructed for a circuit of 200 (or more) volts must have a long thin filament in order that it shall offer sufficient resistance to allow only 30 watts or thereabouts to be expended upon it, and it should be evident that with such a thin filament the loss of carbon would more rapidly involve a complete rupture than when a thicker filament is employed.

It must be remembered that, however large the main conductors may be, they must offer some definite resistance to the current, and must therefore involve, between the machine and the lamps, a certain loss of potential. Let us suppose, for example, that a large room at the limit of the circuit in a private installation takes a current of 50 amperes, and that the resistance of the conductors between the machine and the lamp switch is 0·04 ohm, then the loss of potential in those conductors will be $E = C \times R = 50 \times 0{\cdot}04 =$ 2 volts. Hence a lamp on the dynamo itself would be run at a potential difference of, say, 112 volts, while a lamp in the distant room would have only 110 volts. It is the practice in good installations to allow a maximum fall of potential between the dynamo and the farthest lamp, when all lamps are in circuit, of not more than 2 volts. When the wiring is improperly done, the fall is frequently much higher, and we have come across many cases where it is as much as 8 or even 10 volts. The energy which thus fails to reach the lamps is, of course, wasted in heating the conductors. Such badly proportioned mains are prejudicial in another way. When only a small proportion of the

lamps is in use they will receive almost the full pressure of the machine, and in cases where it is the practice to over-run the dynamo in order to compensate for the loss in the mains, the life of the lamps may easily be shortened by having too strong a current forced through them. It will be shown in the closing chapter how central-station engineers try to overcome this difficulty.

The loss in the mains is easily calculated, as the fall of potential at full load is equal to the maximum current multiplied by the resistance, and the power lost is equal to this fall of potential multiplied by the current.

Assuming an efficiency of 3·5 watts per candle, it follows that 746 watts, or one electrical horse-power, expended in the filaments would produce a light of 213 candle-power, an equivalent to that of thirteen 16-candle-power lamps. But the power developed by the engine in a fairly large private installation is frittered down by the losses in the dynamo, the leads, and the fittings, so that, in practice, not more than ten 16-candle-power lamps can be maintained for each horse-power developed by the engine, while in a public supply system the losses are, for reasons which should be very obvious, still greater.

If we assume that each lamp is made to last 1000 hours—and it will still be a long time before the consumer can be brought to see the advantage of more frequent renewals—then, on a basis of an average of two hours burning per day, the whole of the lamps in an installation would have to be renewed at the end of about eighteen months, so that a 50-lamp installation would cost from 30*s.* to 3*l.* per annum (according to the make) for lamps alone, and this is an item of sufficient importance to have some considerable value in determining whether or not the light shall be adopted. Of course the adoption of metallic-filament lamps will with judicious application alter these conditions materially, as, while the efficiency of the lamps is much higher, their cost is higher, and owing to the absence of blackening, the proportion of the light which gets through the bulb as the lamp ages is greater. Further experience with this class of lamp is necessary before a definite pronouncement can be made, but there is every indication that the life of a metallic filament will exceed that of a carbon filament, and that the former will therefore fully justify its greater cost.

As a matter of fact we know of several installations which, on account of the cost of electric lighting with carbon-filament lamps, would have been turned over to incandescent gas but for the substitution of the more efficient metallic-filament lamps.

When a number of ordinary incandescent lamps are joined in series, the fracture of the filament in one lamp involves the extinguishing of the other lamp or lamps in series with it. If, therefore, all the lamps in a circuit were joined in series, the failure of one lamp would result in a total disconnection of the circuit. The parallel system has, however, many advantages. There is no risk of receiving a serious shock on touching the mains, as the maximum potential difference is only that necessary for one lamp, which, as we have said, usually ranges from 100 to 240 volts. If one of the branch leads should become broken, only the lamps on that branch will be thrown out of use. The means available for connecting the lamp to the supply wires are of the simplest description. The insulation of the mains is a matter of less difficulty than with high potential circuits.

On the other hand the cost, of the mains in a large installation is considerable, and, as we have already pointed out, the maintenance of a constant potential difference throughout an extensive network is a matter of some difficulty, a difficulty which does not attend series working.

Lamps have been constructed for series working—that is to say, on a constant-current circuit—and were usually provided with low resistance filaments, designed to carry a current of 5 or 10 amperes, so that they could be joined up in circuit with ordinary arc lamps. In some circumstances this is a decided advantage — for example, in cases where an arc lamp would at certain hours give more light than is required (and would then involve a waste of energy)—but where total darkness is undesirable, a series incandescent lamp could be joined with an arc lamp to a 'two-way' switch, by turning which either the arc or the incandescent lamp can be thrown in circuit at will, both lamps being constructed to take the same current. Experience seems, however, to have demonstrated that series incandescent lamps are not required, or that the cut-out device to short-circuit the lamp when the filament gives out has not been designed on a sufficiently reliable

basis, and this class of lamp is in consequence a matter of history.

Incandescent lamps are serviceable in a variety of ways. For domestic lighting they know no equal; they in no sense of the word vitiate the air, nor do they consume it; they have very little effect upon the temperature of a room; they are not injurious to furniture, books, or ceiling, and deposit no soot; they can be placed near, but not in contact with, curtains or other combustible material without entailing any risk of fire; they are independent of air currents, which cause flickering in any lamp where gas or oil is burned; they are exceedingly convenient, and can be 'turned on' at any moment without necessitating the use of a match; the switch for turning them on can be placed in any convenient position; and the lamps are incompetent to cause explosions, because the filament is destroyed immediately the bulb is broken. On the other hand, they consume a practically invariable amount of energy, for the light cannot be turned down without the introduction of a shunt, or of resistance, in which the energy which would otherwise be absorbed in the lamp is expended in the development of heat. Of course, where alternating currents are employed a small choking coil may be inserted in the circuit to reduce the pressure at the lamp terminals. This device is serviceable where many lamps have to be 'dimmed' for theatrical or other similar purposes, but it is not generally applicable. Incandescent lamps are, however, not so satisfactory for street lighting unless of high candle-power, for most of the advantages which pertain to them when used in a house disappear when they are taken into the street. The public look for a brilliant light and get only the equivalent of a good gas-jet. Incandescent lamps are readily adaptable to the lighting of railway carriages. They have no equal for ship-lighting, their usual competitors in such cases being bad oil and worse lamps. In the case of passenger steamers expense is not of paramount importance: hence it is not to be wondered at that in this work incandescent electric lighting now reigns supreme. Incandescent lamps should prove of inestimable service in mines and in the bunkers of ships, where the chief difficulties to be contended with are want of portability, and the risk of sparking between the broken ends of

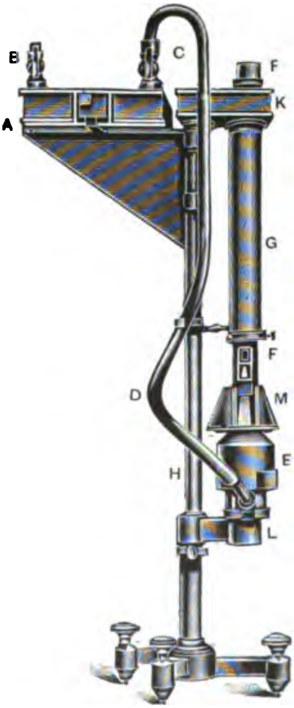
a wire, or at switch contacts. These are matters which are being gradually conquered, and there is but little doubt that before long the Davy and Geordie 'safety' lamps will be relegated to historical museums. There is a scope for incandescent lamps for the use of divers, and in many surgical examinations and operations, as well as for the microscope, the optical lantern, and the picture-gallery.

In order to estimate the amount of light emitted by any luminous source, electric or otherwise, a large number of 'photometers' or light-measurers have been devised, but, excellent as some of these may be in theory, they have, when applied practically, two serious defects. Measurement of every kind requires some unit or standard with which to compare the substance, force, or effect it is desired to measure; and it is pre-eminently essential that this unit or standard shall be fixed and invariable, and that it shall, without very much trouble, be reproducible. The majority of units comply more or less with these requirements; the one unit which does not, which is never fixed, but is always liable to variation, is the so-called unit of light. With us in England the official unit was for a very long time the 'candle-power,' which was assumed to be the light produced by a 'standard candle' weighing six to the pound and made to burn 120 grains of spermaceti wax per hour. There were, however, so many objections to this unit, owing to the variation in the composition of the wax, the texture and composition of the wick, the liability of the flame to fluctuate with variations of the atmospheric conditions, and a host of other sources of error, that much time and labour have been devoted to the production of a suitable and satisfactory unit. This, after much discussion of a more or less acrimonious nature, has resulted, and it is to be hoped terminated, in the adoption of the pentane lamp designed by Mr. Vernon Harcourt. It is a flame lamp, and it should be noted that the special requirements of a standard flame are that the combustible must be of known and definite composition; the conditions of burning must be of a simple and definable character, and the nature of the combustible, as well as the conditions of burning, must be such that atmospheric changes may produce a minimum effect upon the light.

The combustible employed in the Pentane standard lamp consists of a mixture of air with that portion of American petroleum

which, after repeated rectifications, distils at a temperature not exceeding 50° C. This liquid consists almost entirely of pentane, its specific gravity at 15° C. ranging from 0·628 to 0·631. Great care has to be taken in the preparation of the pentane in order to ensure that it shall be free from impurities and of the standard density. Its chemical composition is represented by the symbol C_5H_{16}. The original pentane lamp was designed to equal a standard candle, but the form which is more generally adopted is much larger, and has, in fact, an illuminating power equivalent to ten standard candles. The general construction of the lamp as made by Messrs. Wright & Co. is illustrated in fig. 366.

FIG. 366



It comprises a rectangular box or saturator, A, supported at the top of the tube H, which carries the lamp. Into this is poured liquid pentane in sufficient quantity to fill it up to about two-thirds of its capacity. The pentane gradually volatilises and mixes with air which is admitted by way of the stopcock B. The air is drawn round a number of baffle plates to ensure a satisfactory mixture, and the air-gas emerges through the stopcock C, and passes down the indiarubber tube D to the steatite argand burner E. Delicate adjustments are provided in order to facilitate the proper regulation of the rate of flow through the two stopcocks. Air for combustion purposes is supplied for both the inner and outer surfaces of the flame. There are two double metal chimneys, of which the inner one, F F, protects the flame and carries near its lower end a mica window. Air passes up the annular space between these chimneys and is then conveyed through

the box K to the tube H. Passing down this the heated air enters the bracket L, and then passes up through the burner to the inside of the flame. There is a small cylindrical box, E, which actually encloses the burner above referred to, and air is drawn through this box and heated on its way to the outside of the flame. The lower end of the inner chimney tube, F F, is adjusted by means of a boxwood gauge provided for the purpose to a height of 47 millimetres above the burner. A conical shade, M, is so placed that the whole surface of the flame below the tube F F can be seen through the opening. The lamp requires to be fixed truly vertical, and facilities are provided for ensuring this and other necessary refinements. The flame should be so regulated (by means of B and C) that the tip of it is about midway between the bottom of the mica window and the cross-bar, but it is said that a variation of a quarter of an inch either way does not materially affect the luminosity of the flame, provided, however, that the accuracy required is not greater than about 1 per cent. The proportions which have been given to the various parts of the lamp are, however, such that when the flame is at its correct height its luminosity is a maximum, any variation above or below the correct height causing a decrease in candle-power.

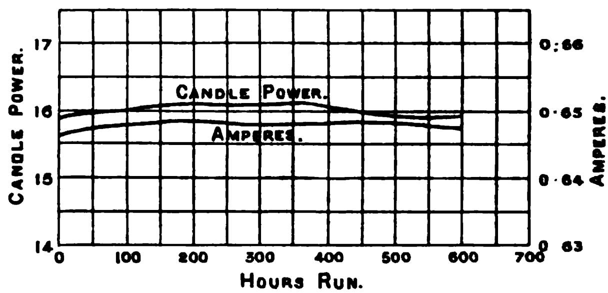
The 10-candle-power pentane standard is much more reliable than the original 1-candle-power lamp which was provided with a wick, and it is more useful because the illuminants, whether gas or incandescent electric lamps, with which it has to be compared, are usually of too high a candle-power to be easily comparable with a 1-candle-power standard. The lamp should be left burning for about fifteen minutes, in order to allow it to become heated, and attain a stable condition before any comparison tests are made with it.

In Germany, the Hefner amyl-acetate lamp has been adopted as the standard, and has, in fact, found much favour both in this country and in America. The lamp is very simple, and carries a cotton-yarn wick saturated with amyl-acetate ($C_7H_{14}O_2$). No chimney is necessary, and the flame, which does not project above the top of the thin German-silver tube which carries it, is so adjusted that it reaches a certain height. The Hefner unit is equal to about 0·9 English standard candle, and this light is

while the advantage of long life, or rather of uniform candle-power, for a prolonged period is almost inestimable. A standard lamp would in ordinary circumstances be used for only a few minutes each day, so that a lamp which had been 'aged,' or run until the period of uniform candle-power is attained, would last for years before the diminution of luminosity sets in, and only occasional re-standardisation would be necessary. The lamps are usually made of 10 or 16 candle-power, and are therefore very suitable for testing lamps of the ordinary or commercial type.

Supposing an absolutely reliable and permanent unit of luminosity to be available, we are still confronted by the second difficulty, viz. the want of a means of accurate measurement. Practical photometers are one and all simple comparison instruments,

FIG. 367



the light emitted by the standard and the source under test being compared simultaneously, and these comparisons must perforce be made by the eye. Unfortunately that organ is untrustworthy as a piece of scientific apparatus, and incapable of accurate discrimination. Its sensitiveness also varies considerably with the individual, so that any series of tests should be taken throughout by the same experimenter, although even then there is some risk of personal error. Of course this difficulty is in a measure overcome by continued practice and attention, but some experiments performed by Professor Schuster illustrate very forcibly the general unreliability of the human eye. He submitted to a considerable number of persons a pure yellow image, and a compound yellow composed of full red and green rays. By means of a 'Nicol

prism,' each person could mix the red and green components together in any proportion; and they were asked to make the compound yellow match the simple colour. The result was extraordinary, for whereas one observer required 2·8 times as much red as green to make the match, another took five times as much green as red to produce the same tint.

All practical photometers are based upon the fundamental law that the intensity of illumination on a given surface varies inversely as a square of its distance from the source of light; and upon the fact that the distances of two independent sources of light can be so adjusted that their illumination of the given surface is equal. Then by measuring these distances the relative illuminating powers can be calculated.

A photometer usually consists of a disc or screen upon which the light rays from the standard and from the lamp under test are allowed to fall, and the distances of the illuminants are adjusted until the luminous effects of the two sources are equal. For example, suppose the distance of the standard (say 1 candle-power) to be 1 foot and that of the lamp $3\frac{1}{2}$ feet when equality of illumination is obtained, then the luminosity is $1^2 : 3\frac{1}{2}^2$; that is to say, the light emitted by the lamp is $12\frac{1}{4}$ times as strong as that from the standard, and it may be called a $12\frac{1}{4}$-candle-power lamp.

The Bunsen or, as it is often called, the 'grease-spot' photometer is an instrument by which fairly accurate results can be obtained; and it is therefore frequently employed. A small screen of somewhat opaque paper is stretched on a metallic ring, which is mounted on a stand movable along a graduated scale. In the earlier forms of this instrument a semi-transparent grease-spot was made in the centre of the disc by means of a little spermaceti dissolved in naphtha, but in later forms the whole of the paper, with the exception of a small central patch, is so saturated. To make an efficient screen is a matter of some difficulty, there being a particular thickness of spermaceti which, with each experimenter, gives the best results.

The standard is fixed at one end of the scale, and the lamp (the luminosity of which is to be measured) at the other end of the scale, which should for convenience be divided into 100, or

some other multiple of 10, equal parts. The two illuminants should be placed at such a height that their centres are in a line with the centre of the screen, which can then be removed along the scale until the spot becomes invisible and the whole of the surface appears to be uniformly lighted; or the screen and standard can be fixed, and the lamp under test moved along the scale to the required point.

The bottom of each of the stands carrying the screen, &c., should be furnished with an index, and, the exact position of these indices on the scale being noted, the relative distances of the two illuminants from the screen can be easily ascertained. Their luminosities can then be calculated by squaring these distances. The principle of this instrument is simple. If a single light is held in front of the screen, the greased paper, which allows a portion of the light falling upon it to be transmitted through it, appears, when viewed from that side on which the light is placed, to be darker than the ungreased portion, which reflects liberally the rays falling upon it. If, on the other hand, the light is placed behind the screen, the grease spot or ring appears as a comparatively bright surface upon a dark ground, owing to the fact that the greased paper transmits a large portion of the light falling upon it, while the other part of the screen transmits scarcely any of the rays. When, therefore, the position of the screen between two sources of light is adjusted until the two sides appear to be equally lighted, the light transmitted by the greased paper will be equal to that reflected from the ungreased paper, and the illumination from the two sources may be taken as equal. As a matter of fact, the grease-spot is never capable of transmitting the whole of the light falling upon it, neither is the ungreased paper a perfect reflector nor absolutely opaque. In order that both sides of the screen may be viewed simultaneously, mirrors should be fixed in position so as to project images of the two sides in one common direction. A number of other refinements may be introduced with a view to securing greater accuracy in the results. One of these is to introduce between the illuminants and the paper screen, screens of cardboard or other opaque material with apertures for the transmission of the direct rays from the sources of light, and to cut off rays reflected from the walls, &c. It is usually stipulated

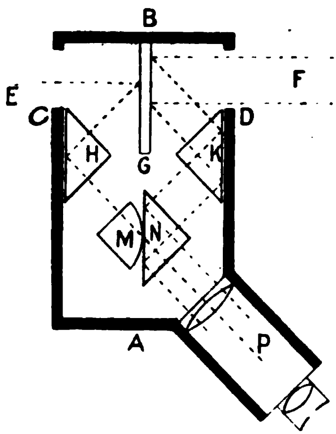
that the walls of the photometer room should be blackened, and that every possible reflecting surface should be similarly treated, but the best blackened surface is still capable of acting as a partial reflector, and Mr. Trotter says that in his photometry work his most valuable assistant was a little piece of looking-glass. If he wanted to ascertain whether any stray rays were falling upon the photometer he simply screened off the direct or legitimate rays, and then explored the neighbourhood in all directions by means of the piece of looking-glass placed in the position occupied by the photometer.

A beam of light falling upon a body is liable to be affected in three different ways: the rays may be transmitted, reflected, or absorbed. Bodies are called transparent when they transmit a large proportion of the rays, but all substances behave more or less as reflectors, for it is only by reflected light that non-luminous bodies become at all visible. All substances also, including even the best reflectors, absorb some of the rays, so that when a reflector is introduced on one side of the measuring apparatus, some difficulty is experienced in estimating the amount of light. This is a feature which has rendered it difficult to produce a simple photometer for the direct measurement of arc lamps and other large illuminants.

Professors Ayrton and Perry, however, designed a photometer of a useful character at a time when there was a great demand for means to measure the light from an arc lamp. Instead of moving the lamp away to a considerable distance in order to compare its light with that of a much feebler standard, a concave lens is employed, which has the effect of scattering or dispersing the luminous rays, and projecting only a few of them upon the screen, whence it is called a 'Dispersion' photometer. As the proportion of the rays thus utilised can be determined, depending, as it does, upon the curvature and absorbing power of the glass, the direct result simply requires to be multiplied by a given constant in order to determine the relative luminosities. A plane mirror is employed to direct the rays upon the lens, the plane of the mirror being always adjusted to an angle of 45° with the incident beam, so as to avoid the introduction of errors due to varying degrees of absorption for different angles of reflection. In another method

of testing arc lamps an incandescent lamp, after being standardised, is employed as a standard, the arc lamp being placed on a scale at right angles with the photometer bar, which carries a mirror adjusted to an angle of 45° with the luminous beam, so as to project the rays upon the disc, the quasi-standard being placed so as to illuminate the opposite side of the disc. The comparison is then made by adding the distance between the disc and the mirror to the distance between the mirror and the arc, and regarding this as the distance which has to be compared with that between the disc and the standard. A constant allowance has to be made for the absorption of the mirror, which for any given angle varies with different samples of glass. It is obviously necessary that the arc should be so screened that none of the rays fall direct upon the disc, and that the angle of the mirror should be kept fixed. Some difficulty is, however, experienced in comparing arc and incandescent lamps owing to the greater percentage of blue rays in the former, and it is only after long practice that the comparison can be made with any degree of confidence.

FIG. 368



It will, perhaps, be understood that the need for measuring the luminosity of arc lamps is confined usually to the laboratory of the experimenter, whereas the testing of every incandescent lamp prior to its sale by the maker is essential if his credit is to be maintained, and if the luminosity of the lamp according to its marking is to be relied upon.

A number of photometers have been constructed in which the design is based on the total reflecting properties of a right-angled prism. Perhaps the most popular photometer of this kind is that known as the Lummer-Brodhun, the construction of which is illustrated in fig. 368. It consists of a metal box, A B, with openings at C and D, through which beams of light,

E and F, pass from the two sources of light to be compared (one source being the particular standard adopted for the experiment). The beams fall upon the white surfaces of a screen of magnesia, G. These surfaces should be kept scrupulously clean, and the light being then fairly diffused, definite proportions will fall upon the right-angled prisms, H K. We have already referred to such prisms, but it may here be mentioned that a beam of light falling at right angles upon one of the shorter faces of such a prism will be totally reflected from the side which forms the hypotenuse of the triangle, and as the angle which the reflected rays make with the reflecting surface is the same as the angle which the incident rays make with that surface, it follows that the reflected rays will emerge from the prisms at right angles with the face at which they emerge. Hence portions of the beams E and F pass through the prisms H and K respectively, and impinge on two more right-angled prisms, M and N. One of these prisms, M, has a portion of its hypotenuse face removed by a sandblast, leaving only a small circular patch untouched. The prisms, M N, are placed together so that the smooth patch on M is placed in optical contact with N, so that at that particular spot the two prisms act optically as a cube, and rays of light coming from the prism H pass straight through M and N and enter the telescope P. Rays from the prism K, which impinge upon the prism N, pass through M where they fall upon the central patch, but where they fall upon the other portions of N they are totally reflected. The observer looking through the telescope sees, therefore, a circular disc of light due to E, surrounded by a ring due to F, the disc being lighter or darker than the ring according to the relative illumination of the two surfaces of the screen G. Assuming F to be the stronger beam, its source is removed until the line of demarcation between the disc and the ring disappears—until, that is to say, the two illuminations are equal, and in such circumstances the luminosity of the two sources will be proportional to the squares of their distances from the screen.

In view of the number of prisms and lenses included in the instrument, and all of which must, to be of any real value, be extremely accurate in construction and very carefully arranged, this photometer can scarcely be regarded as a simple instrument.

Others have been designed on simpler lines for which equal reliability is claimed, but these instruments are usually manipulated by specialists, and, as we have already indicated, photometry is not a physical measurement, but is to a very great extent a matter of judgment. This is especially the case in the measurement of coloured lights or, as it is technically termed, 'heterochromatic' photometry, where the object is to measure the intensity of the illumination independently of the colour.

A photometer room should be fitted with opaque blinds, so that all extraneous rays can be excluded, and when flame standards are employed should be free from draughts and vibration.

A beam of light has two other qualities besides that of illuminating a dark surface. It can easily be shown to possess more or less heat rays; also, that if certain compound substances are interposed in its path, chemical decomposition takes place. Were the three portions of the beams—viz. the thermal, the luminous, and the actinic or chemical rays—always united in the same proportions, we should have no difficulty in constructing a photometer accurate in its measurement and independent of the want of sensitiveness in the eye; for we could, on the one hand, use a thermometer, or a thermopile and delicate galvanometer; or, on the other hand, a piece of sensitised paper, such as is used in photography. But unfortunately the proportions vary considerably.

Tyndall ascertained, as the result of a long series of carefully performed experiments, that the luminous rays from several sources of light bear but a small proportion to the obscure or non-luminous rays, the exact proportion of the former being from

An oil flame	3 per cent.
A gas flame	4 ,,
A white-hot spiral	4·6 ,,
An electric-arc light	10 ,,

The arc light appears here as the richest in luminous rays; it is also the richest in actinic rays, but the poorest in thermal rays. The various proportions differ, however, with different carbons, &c. It has been estimated that of the solar rays about 34 per cent. are luminous. It would be perhaps the greatest single stride of the

century if an artificial source of light were produced from which the whole of the rays were luminous, instead of the great majority being of the lower or thermal order.

In commencing Chapter XV. it was remarked that illumination is the whole object of lighting, and it behoves us now to study, albeit briefly, a few of the points in connection with illumination. By illumination is meant the amount of light falling upon, say, each square foot of the surface to be illuminated, and this amount is of course quite independent of the nature of that surface. The rays which thus fall upon a body may, as we have already indicated, be either reflected, absorbed, or transmitted. It will also be remembered that no surface reflects all the rays incident upon it, nor is any substance so transparent as to transmit all the rays without loss. Such a substance, could we find one, would be invisible, since bodies which are not themselves illuminants or sources of light are seen only by reflected light, and those bodies are brightest which reflect the greatest proportion of the rays which fall upon them. Few, if any, substances are truly white, for to be so they must be capable of reflecting rays of every hue equally. Most bodies, however, absorb rays of one colour more readily than those of another, and such bodies are only visible in virtue of the rays which they reflect. A boiled lobster, for instance, reflects red rays readily, but absorbs the blue rays. If, therefore, it were placed in a room lighted from without, and in lighting which all the rays had to pass through windows of cobalt-blue glass (which absorb the red rays), all the rays incident upon the lobster would be absorbed, and it would therefore be almost black or devoid of colour. If a pinch of salt be burned, it will tinge the room with yellow—that is to say, there will be such a preponderance of yellow rays that every object capable of reflecting yellow rays will assume that hue. Although, therefore, we may measure the illumination of a body by the quantity of light falling upon it, we must estimate the visibility or luminosity of such a body by the proportion of the illuminating rays which are reflected from it, and on p. 777 we give a table of the reflecting powers of a number of substances. Most objects are viewed by diffused light—that is to say, by rays which have been reflected from surface to surface several times before they reach the eye. The best

example of this is sunlight. The solar rays are reflected from roads, houses, &c., into the rooms, and from object to object in those rooms, suffering perhaps hundreds of reflections before they finally impinge upon the retina. It will be manifest that were we dependent upon the direct illumination of objects by the sun, rooms facing due north would be in perennial darkness, while on a cloudy day we should be altogether without light other than that derived from artificial sources.

The illumination of a body depends upon two factors, viz. the quantity of light emitted by the illuminant, and the distance between that illuminant and the body illuminated. The unit of illumination which is more generally accepted is the *candle-foot*, and it is that amount of light emitted by a standard candle (or its equivalent) which falls upon a body at a distance of one foot from it; as the intensity of light varies inversely as the square of the distance from the source of light, it follows that were an object placed at a distance of two feet from a standard candle its illumination would be one-quarter of a candle-foot. One candle-foot is a convenient illumination for comfortable reading. It has been estimated by Mr. Trotter that the illumination due to the sun on a bright day in the streets of London is equal to thirty candle-feet, while the maximum usually obtained in a street lighted by arc lamps is, on the pavement, but little in excess of one-half of a candle-foot. In some recent experiments in London with flame arcs a much better illumination has been attained, both in intensity and in uniformity.

The number and distribution of incandescent lamps to be employed in lighting any given room or building is a matter of some importance, although the efficiency is frequently governed to a very great extent by local requirements, structural details, and questions of taste. Accordingly, it is essential that the installation engineer, to be successful, should have a certain amount of artistic instinct, and it is to the absence of this that the want of effectiveness so frequently seen in installations is to be attributed. Naturally the man who designs the installation is before all things an engineer, and one whose chief object is to get the greatest amount of light for a given expenditure of energy, so that unless a desire is definitely expressed to the

contrary, naked, clear-glass bulbs are almost sure to be used, and frequently so arranged that the intensely brilliant and often dazzling filament directs its rays on to the face of the occupant of the room. For internal domestic lighting no one would employ a naked gas-flame, and it is not at all exceptional for the globes which are usually employed to absorb 60 or even 75 per cent. of the light emitted, and electric-light engineers should reconcile themselves to this, and be content to sacrifice something to comfort and appearance. It is not at all fair to compare an unscreened incandescent lamp with a shaded gas-flame, and say that the 16-candle-power incandescent lamp gives out two, three, or four times as much light as the gas-flame. Nevertheless, this manifestly objectionable comparison is frequently made. As the intensity of illumination varies inversely as the square of the distance from the illuminant, it will often become a serious question whether it is preferable to place unscreened lamps with reflecting shades high up, or to place screened lamps, or lamps with 'frosted' bulbs, low down. Or again, more especially in small rooms, a more uniform distribution of light will be obtained from four 8-candle-power lamps than from two of 16 candle-power, although the prime cost for wiring and fittings will be heavier. An obscured or frosted globe, although it absorbs more of the rays than does a clear globe, gives a better effect, and as the pupil of the eye contracts when looking at the comparatively dazzling light of the unscreened filament, it is possible that the number of rays which actually enter the eye will differ but little in the two cases. The filament in a frosted lamp is invisible, and the comparatively large bulb looks very much as though it is in reality the source of light, and the luminous area being thus enlarged the luminous intensity is reduced and the contrast between the source of light and the lighted objects is less striking. With an ordinary unscreened gas-flame a room looks very poorly lighted in comparison with the effect produced by placing a globe over the burner, although we know as a matter of fact that there is less light emitted in the latter case than in the former. Moreover, the distribution from a lamp with a ground-glass bulb is very different from that obtained with a clear one. We may, in fact, look upon a sheet of ground glass as being composed of an almost infinite

number of small and irregular prisms. Rays from every point of the filament impinge upon every portion of the glass, and then, passing through different thicknesses of the bulb, they undergo refraction to such an extent that practically each little prism becomes a separate and distinct source of light, its rays passing out in every conceivable direction. Of course, if the lamp is actually out of the range of the eye, clear globes should be used, so that the objects in the room, which have no contracting pupil and which are seen only by reflected light, may receive the maximum number of rays.

It does not always follow that anything approaching very closely to uniformity in illumination is required for internal work. For example, in an office the light is wanted over the tables or desks, and not on the floor between them; in dining-rooms the light is required over the tables rather than on the walls. Where uniform illumination is required in a room with fairly light walls, and with lamps seven and a half or eight feet above the floor, a good rough rule is to allow, in the case of carbon-filament lamps, from three-quarters to one watt per square foot of floor space. With lamps of good average efficiency the smaller value is sufficient for comfortable reading. On the 1-watt basis a room would require a 16-candle-power lamp for every sixty square feet of floor space—assuming, that is, that this lamp takes 60 watts. A great deal, however, depends upon the colour and surface of the surroundings. Dull and dark surfaces absorb a very large proportion of the luminous rays which impinge upon them and convert them into heat, while light and smooth surfaces reflect them freely, and by repeated reflections add considerably to the illumination of the room. Dr. Sumpner has published the table reproduced on the next page showing the reflecting powers of a number of substances with which he experimented.

It thus appears, says Dr. Sumpner, that even a dull-looking wall will reflect as much as 20 per cent. of the light incident upon it. A wall of ordinary tint reflects from 40 to 50 per cent., while a good white surface reflects over 80 per cent. A clean white-washed ceiling reflects as much light as an ordinary mirror, for although extremely good mirrors may be obtained which will reflect as much as 90 per cent. of the light incident upon them,

measurements made with common mirrors do not show a greater reflecting power than 82 per cent. A room with its surfaces well whitewashed thus needs only one-fifth of the candle-power to produce any given amount of illumination that it would need if its walls, ceiling, &c., were all painted black.

The student will not, therefore, be surprised to learn that it is no unusual experience to find that while one room may be uniformly well lighted with an expenditure of three-quarters of a watt per square foot, another room will be but dimly lighted with an expenditure of $1\frac{1}{2}$ or even 2 watts.

TABLE OF REFLECTING POWERS

	Per cent.		Per cent.
White blotting paper	82	Tissue paper (one thickness)	40
White cartridge paper	80	,, ,, (two thicknesses)	55
Tracing cloth	35	Yellow wall-paper	40
Tracing paper	22	Blue paper	25
Ordinary foolscap	70	Dark-brown paper	13
Newspapers	50 to 70	Deep chocolate-coloured paper	4
Plain deal (clean)	40 to 50	Yellow painted wall (dirty)	20
,, ,, (dirty)	20	,, ,, ,, (clean)	40
Yellow cardboard	30	Black cloth	1·2
Parchment (one thickness)	22	Black velvet	0·4
,, (two thicknesses)	35		

CHAPTER XVII

INSTALLATION EQUIPMENT, FITTINGS, ETC.

ONE of the most important details to be considered in connection with an electric light or power plant is the means to be adopted for transferring the energy from the generator to the lamp or motor.

In electric lighting, copper is always employed for the conductor. The current to be carried is usually heavy, and it is imperative that the loss of energy due to the resistance of the conductor should be brought down to the lowest practicable limit. Were iron to be employed, it would be necessary to give it six times the sectional area of the copper to obtain the same conductivity, and in addition to the difficulty in handling such heavy conductors and jointing them together, the cost of providing effective insulation would be very great. In fact, an iron conductor sheathed with insulating material would be considerably more expensive than one of copper offering the same resistance, and in any case iron would be quite unsuitable for use with rapidly alternating currents.

It will be seen, from a study of the table given on p. 18, that the choice of materials for electrical conductors of any kind is really limited to the two metals above mentioned, viz. copper and iron; so that for electric-lighting work we have no alternative but to use copper.

For electric railways, however, where bare conductors are employed supported by 'insulators' resting on the sleepers, the question of specific resistance is not a determining factor, and iron or rather mild steel of special cross-section is generally employed. The cost of the copper, which would have to be provided in sufficient mass to withstand the wear and tear of the

trailers, would be prohibitive, and the temptation to illicitly acquire heavy pieces of valuable metal would be too great. For electric tramways and other power purposes where the conductor is suspended on poles, or insulated for laying in subterranean conduits, copper is always used.

The accompanying tables (pages 780, 781) concerning the various sizes of copper wire generally employed give some instructive details. It will be seen that the conductors referred to in the second table are made up of a number of comparatively small wires stranded together, the chief objects being to impart greater flexibility and to reduce the risk of complete fracture.

Now, as in overcoming the resistance of a conductor electrical power is wasted, and as it costs money to develop electrical power, it is evident that in any commercial system such waste must be kept down to a minimum. This can be done by simply reducing the resistance: that is, by increasing the size of the conducting wires; but as this also is an expensive matter, care must be taken that the addition thus made to the expenditure in conductors is not so great as to more than counterbalance the cost of the power continually being saved. It has been laid down as a general rule that, for the transmission of any given current, the size of the conductor most economical to employ is one offering such a resistance that the cost of the energy wasted per annum in heating the conductors should be approximately equal to the interest per annum on the original outlay upon them. Knowing the average current to be transmitted, it becomes easy to find the average electrical horse-power wasted in a conductor of any given resistance; but the cost of developing a horse-power depends upon many conditions, principally local, such as the cost of fuel, attendance, rental, repairs, prime cost and efficiency of the plant. And with regard to the conductors themselves, it must be remembered that it is not merely a question of the quantity and price of the metal employed, but also of the insulation and laying.

Most main conductors for lighting purposes are, in England, placed underground, and in many cases the cost of insulating and laying considerably exceeds the actual cost of the wire. Further, although the resistance of a wire one inch in diameter is only one-

fourth of that of a wire half an inch in diameter, it does not cost anything like four times as much, nor even twice as much, to lay the thicker wire as it does to lay the thinner, for the labour of

Table of Annealed Copper Wires

Standard Gauge	Diameter		Sectional Area		Weight		Resistance at 60° F.	
	Inches	Millimetres	Square inches	Square millimetres	Lbs. per mile	Kilogrammes per kilometre	Ohms per mile	Ohms per kilometre
7/0	·5000	12·70	·1963	126·7	3996·	1126·0	·2155	[illegible]
6/0	·4640	11·79	·1691	109·1	3441·	969·9	·2502	[illegible]
5/0	·4320	10·97	·1466	94·56	2983·	840·7	·2887	[illegible]
4/0	·4000	10·16	·1257	81·07	2557·	720·8	·3367	[illegible]
3/0	·3720	9·449	·1087	70·12	2212·	623·4	·3893	[illegible]
2/0	·3480	8·839	·09511	61·36	1936·	545·6	·4448	[illegible]
1/0	·3240	8·229	·08245	53·19	1678·	472·9	·5132	[illegible]
1	·3000	7·620	·07069	45·60	1438·	405·4	·5986	[illegible]
2	·2760	7·010	·05983	38·60	1218·	343·2	·7072	[illegible]
3	·2520	6·401	·04988	32·18	1015·	286·1	·8483	[illegible]
4	·2320	5·893	·04227	27·27	860·3	242·5	1·001	[illegible]
5	·2120	5·385	·03530	22·77	718·3	202·5	1·199	[illegible]
6	·1920	4·877	·02895	18·68	589·2	166·1	1·461	[illegible]
7	·1760	4·470	·02433	15·70	495·1	139·5	1·739	[illegible]
8	·1600	4·064	·02011	12·97	409·2	115·3	2·104	[illegible]
9	·1440	3·658	·01629	10·51	331·4	93·41	2·598	1·614
10	·1280	3·251	·01287	8·302	261·9	73·81	3·288	2·043
11	·1160	2·946	·01057	6·818	215·1	60·62	4·004	[illegible]
12	·1040	2·642	·008495	5·480	172·9	48·72	4·981	[illegible]
13	·0920	2·337	·006648	4·289	135·3	38·13	6·365	[illegible]
14	·0800	2·032	·005027	3·243	102·3	28·83	8·418	[illegible]
15	·0720	1·829	·004072	2·627	82·86	23·35	10·39	[illegible]
16	·0640	1·626	·003217	2·075	65·47	18·45	13·15	[illegible]
17	·0560	1·422	·002463	1·589	50·12	14·13	17·18	10·67
18	·0480	1·219	·001810	1·167	36·82	10·38	23·38	14·53
19	·0400	1·016	·001257	·8107	25·57	7·208	33·67	20·92
20	·0360	·9144	001018	·6567	20·71	5·838	41·57	25·83
21	·0320	·8128	·0008042	·5189	16·37	4·613	52·61	32·69
22	·0280	·7112	·0006158	·3972	12·53	3·532	68·71	42·70
23	·0240	·6096	·0004524	·2919	9·206	2·595	93·53	58·12
24	·0220	·5588	·0003801	·2452	7·736	2·180	111·3	69·16
25	·0200	·5080	·0003142	·2027	6·393	1·802	134·7	83·69
26	·0180	·4572	·0002545	·1642	5·178	1·460	166·3	103·3
27	·0164	·4166	·0002112	·1363	4·299	1·212	200·3	124·5
28	·0148	·3759	·0001720	·1110	3·501	·9867	245·9	152·8
29	·0136	·3454	·0001453	·09372	2·956	·8332	291·3	181·0
30	·0124	·3150	·0001208	·07791	2·458	·6927	350·4	217·7
31	·0116	·2946	·0001057	·06818	2·151	·6062	400·4	248·8
32	·0108	·2743	·00009161	·05910	1·864	·5254	461·9	287·0
33	·0100	·2540	·00007854	·05067	1·598	·4505	538·7	334·8
34	·0092	·2337	·00006648	·04289	1·353	·3813	636·5	395·5
35	·0084	·2134	·00005542	·03575	1·128	·3179	763·5	474·4
36	·0076	·1930	·00004536	·02927	·9232	·2602	932·7	579·6
37	·0068	·1727	·00003632	·02343	·7390	·2083	1165·	723·9
38	·0060	·1524	·00002827	·01824	·5754	·1622	1496·	929·9
39	·0052	·1321	·00002124	·01370	·4322	·1218	1992·	1238·
40	·0048	·1219	·00001810	·01167	·3682	·1038	2338·	1453·

Table of Stranded Conductors

Number of wires in strand	Standard gauge of each wire	Diameter (in inches): Of each single wire	Diameter (in inches): Of the strand	Equivalent to solid wire: Diameter (inches)	Equivalent to solid wire: Area (square inches)	Weight of Conductor per statute mile (lb.)	Resistance at 60° Fahr. per mile (ohms)
3	25	·020	·043	·0345	·00093	19·42	45·45
3	24	·022	·047	·0378	·00112	23·49	37·55
3	23	·024	·052	·0414	·00134	27·96	31·57
3	22	·028	·060	·0482	·00182	38·05	23·19
3	21	·032	·069	·0552	·00238	49·71	17·75
3	20	·036	·078	·0621	·00301	62·92	14·03
7	25	·020	·060	·0527	·00217	45·23	19·44
7	24	·022	·066	·0579	·00263	54·71	16·07
7	23	·024	·072	·0632	·00313	65·12	13·50
7	22	·028	·084	·0737	·00426	88·63	9·920
7	21½	·030	·090	·0790	·00489	101·8	8·643
7	21	·032	·096	·0842	·00557	115·8	7·596
7	20½	·033	·099	·0868	·00592	123·2	7·143
7	20	·036	·108	·0948	·00705	146·6	6·001
7	19	·040	·120	·1053	·00870	180·9	4·860
7	18	·048	·144	·1264	·01254	260·5	3·375
7	17	·056	·168	·1475	·01706	354·5	2·480
7	16	·064	·192	·1684	·02227	463·1	1·900
7	15	·072	·216	·1896	·02822	586·2	1·500
7	14	·080	·240	·2106	·03484	723·6	1·215
19	22	·028	·140	·1215	·01157	240·8	3·659
19	21	·032	·160	·1386	·01510	314·6	2·802
19	20	·036	·180	·156	·01912	393·3	2·213
19	19	·040	·200	·173	·02360	491·7	1·793
19	18	·048	·240	·208	·03399	707·9	1·245
19	17	·056	·280	·243	·04627	963·3	·9147
19	16	·064	·320	·277	·06039	1258	·7007
19	15	·072	·360	·312	·07650	1593	·5532
19	14	·080	·400	·347	·09442	1966	·4482
37	20	·036	·252	·218	·03722	775·8	1·137
37	19	·040	·280	·242	·04596	957·9	·9208
37	18	·048	·336	·290	·06619	1379	·6394
37	17	·056	·392	·339	·09006	1877	·4699
37	16	·064	·448	·387	·1176	2451	·3599
37	15	·072	·504	·435	·1489	3103	·2842
37	14	·080	·560	·484	·1838	3830	·2305
61	18	·048	·432	·373	·1091	2274	·3879
61	17	·056	·504	·435	·1485	3094	·2850
61	16	·064	·576	·497	·1939	4042	·2183
61	15	·072	·648	·559	·2455	5116	·1724
61	14	·080	·720	·621	·3029	6316	·1397
61	13	·092	·828	·714	·4008	8353	·1056
61	12	·104	·936	·808	·5120	10674	·08266
91	14	·080	·880	·759	·4519	9422	·09364
91	13	·092	1·012	·872	·5977	12462	·07080
91	12	·104	1·144	·986	·7638	15925	·05541
91	11	·116	1·276	1·100	·9504	19811	·04453

trenching and re-instatement would be the same in both cases. The insulation and mechanical protection of the conductor are important and expensive items, which do not increase so rapidly as the resistance of a wire is reduced by an increase in its size: so that it does not by any means follow that a given reduction in resistance entails a proportionate increase in expense, and it becomes impossible to lay down any hard and fast rule which shall determine the exact size of conductor for any given case.

It may be noticed incidentally, that when the diameter of a round conductor is doubled, although its sectional area, and therefore its conductivity, is increased fourfold, its surface is only doubled. Therefore, if a current of four times the strength is passed through it, the heat developed will be four times as great (since power wasted = C^2R), while the surface at which radiation takes place has only been doubled. The temperature of the thicker wire will consequently rise higher than that of the thinner one when they carry currents in proportion to their conductivities. A wire employed for the purpose of transmitting current to lamps or motors should never be so small that the maximum current transmitted can appreciably raise its temperature; but for other special cases it may be noted that one advantage attending the use of bare conductors is the greater facility afforded by them for the radiation of heat as compared with covered conductors.

So many considerations, mostly special for every particular case, enter into the question of the best size and shape of the conductor consistent with strict economy, that we cannot discuss the matter fully here. But with regard to the reduction of resistance by the employment of high conductivity copper, it should be noticed that, as the presence of a minute quantity of foreign matter causes such a great increase in the resistance of this metal, it is *always* economical when copper is selected to use the purest metal obtainable commercially.

In systems of distribution of electrical power by means of a constant current, the question is comparatively simple, as the current employed is not a heavy one, and it has the same value at all times and in all parts of the circuit. The chief difficulty likely to arise is in providing for future extensions of the system when

the potential difference which can be applied at the ends of the circuit is limited.

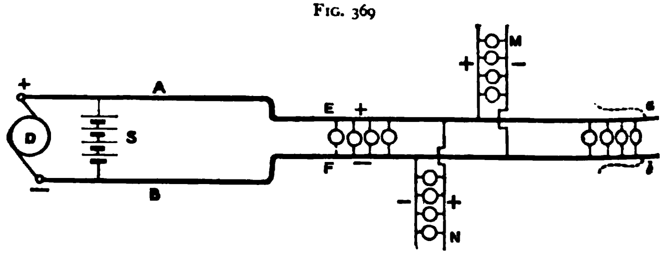
The more interesting and more difficult problem consists in the supply of current to lamps, or other apparatus, at a constant potential; for then the main conductors have to carry a very heavy and variable current. The matter becomes even more difficult if the lamps are distributed over a wide area, or are situated at a distance from the generating station. As has been pointed out in Chapter XIII., the power wasted may in such cases be reduced to a minimum, by transmitting it in the form of a small current at high pressure, and reducing the pressure at the required point to a suitable value. But such a system has its disadvantages. Although the cost of the copper is greatly reduced, the high potential difference employed demands very efficient and expensive insulation, the engines and dynamos must always be kept running, and when very little power is being demanded, the efficiency of the transformers and of the whole system falls. It is true that when the secondary circuit of a parallel transformer is disconnected or only lightly loaded, the transformer absorbs but a small proportion of its full power, because the primary current is then of low value and also nearly 90° in phase behind the impressed E.M.F.; but the energy lost in eddy currents and hysteresis is practically the same as at full load, and of course the difference in phase referred to does not reduce the loss in heating the main conductors and the primary coils of the transformers. When the number of transformers is large, the total power thus wasted becomes considerable during the times when little or no light is required—that is to say, during the greater part of the twenty-four hours.

In the method of distribution by means of continuous currents led direct from the dynamo to a number of lamps all joined up in parallel, the chief problems to be faced are the heavy loss occurring in the mains, and the difficulty of regulating the pressure at the terminals of each lamp. Such a system is indicated by the diagram in fig. 369, where D represents a dynamo capable of maintaining a constant potential difference at its terminals; A and B, the main leads from the machine to the nearest lamp; and E, F the continuation of those leads, between which the lamps are placed. Suppose there to be 100 lamps so joined in parallel,

each requiring a current of half an ampere, and a potential difference at its extremities of 110 volts. The total current supplied by the dynamo with all the lamps in use would be 50 amperes, and this current would have to be carried by the main leads A and B. Supposing the resistance of A and B to be one-tenth of an ohm, the power wasted in overcoming this resistance would be 250 watts, and the consequent fall of potential 5 volts. Therefore the machine must develop at least 115 volts at its terminals in order to maintain 110 volts at the *nearest* lamp.

Now a further fall of potential would take place along the more distant mains E, F; suppose this to amount to 10 volts, then the pressure at the most distant lamp would only be 100 volts, while if this were raised to the desired value of 110 volts by

FIG. 369



an increase at the dynamo, the nearest lamp would then be working at 120 volts, or 10 volts above its proper pressure. Even ignoring the waste of power, such a difference could not be permitted if similar lamps were used throughout the system, as some would be giving far above and others far below their normal candle-power.

It would, however, be practicable, but to some extent inconvenient, to employ different types of lamp, placing those made to run at 110 volts at the end near the dynamo, and others constructed for 100 volts at the farther end of the line, and so on. But even then, if the dynamo were perfectly regulating—that is to say, capable of maintaining a constant potential difference at the brushes under all circumstances—the potential at the far end of the mains would rise considerably when any number of the nearer or intermediate lamps were cut out of circuit. It is, however, the

practice for some central-station engineers to ascertain the average potential difference in the various sections of the network, and to recommend consumers to provide lamps accordingly.

Referring again to the figure, it will be observed that the mains at any one point only carry a current equal to that required by all the lamps beyond that point. Thus, while the portions A B take the whole current, those portions between the last lamp and the last but one carry only half an ampere. The size of the mains might, therefore, be reduced by one hundredth as every lamp is passed, and the same density of current in the conductor be retained. This is equivalent to bunching 100 wires together to form the main, and taking out one of them at every lamp. If the 100 wires were separately insulated—that is to say, if a separate lead and return wire were used between the machine terminals and each lamp—the pressure at the ends of these leads would be constant; and since the resistance in each independent lamp circuit is also constant, the pressure at each lamp would be unaltered by any variation in the number thrown in circuit. This forms a means of maintaining a perfect regulation, although of course the actual pressure at the lamp would depend upon the resistance of its particular leads. Great as are the advantages of such a method, the expense would forbid its being employed in an installation extending over a large area. It will be seen, however, that with ordinary mains if the resistance is sufficiently low to make the fall of potential very small, then the variation which would take place in the potential difference at the extreme end of the circuit becomes negligibly small. An extreme variation of 2 volts might be allowed, and then, by maintaining the normal pressure of 110 volts near the middle of the system, the nearest lamp would have but 111 volts and the farthest 109.

It is necessary to be able to observe in the engine-room the pressure existing at the far and near ends of the mains at any moment, so as to be able to keep one point as much below as the other is above the normal pressure; and this can be done by leading 'pilot-wires' from the mains at those points to a voltmeter placed at the generating station.

For instance, in fig. 369 a thin wire might be led from the point *a* and another from *b*, each to one terminal of the volt-

meter, which would afford an indication of every variation at the extreme end of the mains. A second pair of pilot-wires might be led from the nearest lamp; or by leading one pair only, connected to the mains at the centre of the system, and keeping the potential there at 110 volts, a good average regulation might be maintained.

At many of our supply stations where several thousand lamps are supplied in parallel, batteries of secondary cells are used in conjunction with the dynamos, for regulating and assisting the machines to meet an exceptionally large demand. At the extreme ends of all the mains a standard pressure is maintained, while that at the nearest lamp does not exceed that pressure by more than two or three volts. A pair of thin wires is led, as mentioned above, from the end of the mains to a voltmeter in the engine-house, and when this instrument indicates a fall of potential (caused by the switching in of more lamps) the attendant immediately switches one or more secondary cells on to that pair of mains, in series with the existing cells, thus raising the pressure to the required value; the cells being of course cut out when the voltmeter indicates a rise of potential.

Although on a simple parallel system of distribution, the arrangement is such that the whole of the lamps are connected in parallel between the two mains, it is evidently impracticable to join them directly across (as indicated in the case of the nearest and farthest lamps in fig. 369) when the mains are carried under the roadway. It is necessary to lead a wire from each main to every group of lamps, say to every house supplied, in the manner indicated at M, N. The higher potential mains are throughout marked +, and the lower potential, or return wires, —. These subsidiary mains should be proportioned in size according to the number of lamps to be supplied by them.

It is not practicable, however, to sufficiently reduce the resistance of a single pair of mains leading direct from the dynamo to maintain even approximately a constant pressure at all the lamps if they are distributed over a large area; a method of facilitating regulation in such a case, by the employment of subsidiary mains which feed the mains proper at certain points, but are not themselves tapped by lamp circuits, has already

been described in connection with transformers, and will again be referred to later on.

The method of employing a battery of secondary cells so as to assist in the regulation, or in the maintenance of a constant potential, is indicated in fig. 369, where S represents such a battery. The cells are joined in parallel with the dynamo, and are charged by it without any alteration in the connections other than those indicated in Chapter XIV. being necessitated.

The interactions between the dynamo and the battery may be embraced under three heads. (*a*) When the E.M.F. of the battery is less than the potential difference at the dynamo terminals, the machine is supplying current to the lamps and at the same time charging the cells, the strength of the current passing through the cells depending upon the excess of the potential difference maintained by the machine over the E.M.F. of the cells. (*b*) When the E.M.F. of the cells becomes equal to the potential difference at the machine terminals, both generators are equally active in feeding the lamp circuit. (*c*) When the E.M.F. of the cells rises above the normal—that is, above that potential difference which is required to be maintained at the terminals of the generators in order to maintain the right pressure at the lamps—then the battery not only feeds the lamp-circuit, but raises the pressure at the machine terminals. This rarely happens, but, the machine being shunt-wound, the effect is to increase the current through the field coils, giving a stronger field, which again tends to increase the E.M.F. developed. When the potential difference thus rises, it becomes necessary tc cut out one or two cells to prevent the pressure rising sufficiently high to injure the lamps. Suitable switches (such as that illustrated in fig. 312) are employed for this purpose, and the regulation effected by an attendant in accordance with the indications of the voltmeter.

It will be remembered that if the engine should break down, the cells would drive the shunt machine as a motor in the same direction; but an automatic cut-out should be provided to disconnect the dynamo when the back-current from the cells exceeds a certain limit. A piece of apparatus capable of performing these operations was described in Chapter XIV.; it disconnects the machine when from any cause its potential difference falls

below the E.M.F. of the cells. Under such circumstances the cells would be called upon, and should be able, to run even the whole of the lamps connected to the battery for a short period.

It also becomes possible to economise power and the expense of attendance, where only one machine is in use, by running it during the hours when the demand is near the maximum, allowing the cells to supply current to the comparatively few lamps required at other times.

It may occur to the student that a considerable saving in the mains would be effected by joining groups of lamps in series between the mains, all the groups being thus placed in parallel. This is so; for if the lamps were placed in sets of four in series, the potential difference between the mains would be four times that at the ends of one lamp, say 400 volts instead of 100. By this means the maximum current in the mains would be reduced to one-fourth, and the weight of copper correspondingly reduced to give the same rate of loss of power.

But some serious difficulties arise in connection with such a system; for instance, if the filament of one lamp in a set breaks, the other three lamps in that set are immediately extinguished: and if, to remedy this, the faulty lamp is merely short-circuited, the remaining three get too much current, and may also be damaged. Of course a device may be adopted to automatically switch in a second lamp, or to replace the broken one by a resistance equal to it; but the latter arrangement is undesirable on account of the waste of power; and in either case the extra fittings involve additional trouble and expense. The same objection arises in the ordinary case of switching out one of a batch of lamps.

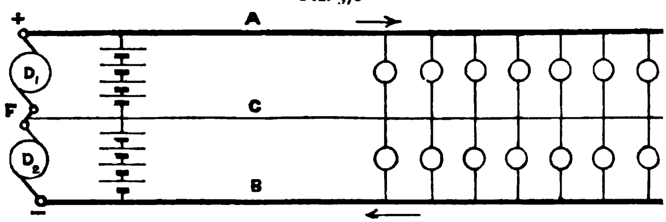
But even if the lamps are joined in sets of only two in series, a considerable saving is effected; and a method by which this can be done, without introducing any of the difficulties referred to, is indicated by the diagram in fig. 370. It is known as the 'three-wire system,' and was devised by the late Dr. Hopkinson.

Two equal dynamos, D_1, D_2, are joined in series, and connected to the mains, A, B, in the ordinary manner. That is to say, the positive terminal of D_1 is joined to the positive main A, and the

negative terminal of D_2 to the main B, while the negative terminal of D_1 is coupled to the positive of D_2. Suppose each machine to be capable of maintaining a potential difference of 110 volts; then when they are so joined in series they maintain the mains A and B at a difference of 220 volts. The lamps being joined, two in series, across the mains as indicated, the potential difference at the extremities of one of them is 110 volts. A third or 'middle' wire, C, which may be smaller than the mains or 'outers,' connects the junctions of the pairs of lamps, and is also joined to the junction of the dynamos.

Now when the number of lamps between A and C is the same as the number between B and C, the potential is the same at every point along the wire C. Hence there is no tendency for any current to flow along the middle wire; it might, in fact, be cut at

FIG. 370



any point, or removed altogether, without in any way affecting the working of the system. But when the lamps on either side of it are made unequal in number this state of balance no longer exists. Suppose a lamp between A and C to be switched out of circuit; then the resistance between A and C is greater, and therefore the fall of potential becomes greater, than between B and C. But the mains A and B are kept at approximately the same potential difference, and if the difference between A and C is increased, it can only be by the lowering of the potential of C. The effect of cutting out a lamp between A and C, then, will be to lower the potential of C near the point where the lamp is disconnected. But the potential at the point F remains unaltered; consequently this difference of potential establishes a current along the wire C, from the junction of the machines to the lamps. The

strength of the current is equal to that which flows through one lamp circuit; it may, in fact, be considered as the current which passes through the additional lamp between B and C. If a lamp between B and C is now switched out, balance is again restored, and no current passes along C. When the number between A and C is made the greater, the difference between those leads is lessened—that is, the potential of C near the lamp is raised. This determines the flow of a current *from* the lamp to the junction of the machines along the middle wire. If the whole of one set of lamps were cut out then the middle wire would have to carry the current supplied to all the lamps in the remaining set, in which case it would require to be as large as the other mains; in some cases the three mains are made equal, but it is usually possible to arrange or 'balance' the lamps so that this extreme case would never happen, the general practice being to give the middle wire about half the cross-section (*i.e.* one-fourth of the resistance) of the outer wires.

Secondary cells may be employed in conjunction with the machines, as indicated in the diagram; two complete sets of cells are needed, their positive and negative terminals being connected to the mains and to the centre wire in the same manner as are the dynamo terminals. The principle may be extended to a five-wire system; but such methods of distribution should only be adopted when the area to be lighted is sufficiently extensive to enable the saving effected in the cost of the mains to much more than balance the disadvantages due to the increase in the cost of the plant and to the additional complications.

A secondary battery may also be utilised to dispense with one of the dynamos. Suppose, for example, a single machine developing 260 volts to be applied to a battery of 110 cells, then the middle wire would start from the centre of the battery, the outer wires being joined to its extremities and to the dynamo.

Owing to the operation of the law that the loss of power in conductors is proportional to C^2R, the saving in copper consequent upon the adoption of the three-wire system is much greater than would at first sight appear. Referring to fig. 369, let us suppose that the conductors A B have to supply current for 100 lamps taking 0·5 ampere each. The current (C) in A B will be 50 amperes. If we suppose the same lamps to be transferred to a three-wire

system and that the load is evenly balanced, the current will be reduced to 25 amperes, or $\frac{1}{2}$ C. In order, therefore, that the loss on the three-wire system shall equal that on the two-wire system we must increase the resistance of the outer mains to four times the previous value, so that $C^2R = \frac{1}{2} C^2 \times 4R$, that is to say, instead of sending a current of 50 amperes through leads offering a resistance of, say, 0·2 ohm, we shall have to send a current of 25 amperes through a resistance of 0·8 ohm. The amount of copper in the outers is therefore reduced to one-fourth, and if the middle wire has one-fourth of the conductivity of the outers we have to add $\frac{1}{32}$ part of the weight of the conductors on the two-wire system. In other words, the weight of copper is reduced under the three-wire system to about $25 + 3 = 28$ per cent. of the weight required on the two-wire system.

A means of reducing the difficulty of maintaining a uniform potential difference along lengthy mains is afforded by the use of independent conductors connecting various points in the circuit direct with the generating station, and these subsidiary leads are termed 'feeders.' In some cases the mains themselves are not connected direct with the generator, but they are arranged to form with the lamp circuit a distinct network, and the whole of the current is supplied to the mains at suitable points by way of the feeders. Experience has shown that in very extensive systems the best practice is to divide the network into a number of groups controlled independently from the central station, rather than to interlace the whole system into a single network by cross conductors. In one notable case where a fire occurred and put the network to earth, the whole area was thrown into darkness, and much trouble was experienced in locating the fault. Had the network been divided into sections, the protective device for the defective section would have indicated at once the particular part of the area where the fault lay, and at the same time the rest of the area could have been supplied without difficulty.

When the potential difference at or near the particular point to which a pair of feeders is connected varies (as it does with a change in the number of lamps in use), this difference is compensated for by correspondingly varying the pressure applied to those feeders, or by some other means varying the current

passing through them. When, for instance, the number of lamps in circuit is increased, the pressure between the mains falls, and more current is required to be supplied by the feeders, and *vice versa*.

It becomes necessary, therefore, to provide some means for promptly indicating, at the generating station, the variations of the potential difference at the points where the feeders join the mains. This is readily supplied by the employment of pilot wires, after the manner already described, so that when a fall of potential in the vicinity of the point at which a particular pair of feeders joins the main is indicated, the electrical pressure along that pair of feeders can be augmented until the distant point is raised to the required standard. On the other hand, should the potential difference in the mains rise, then that on the feeders must be reduced. But economical adjustment in this way is somewhat difficult of attainment. It would, for example, be hardly practicable, except in very large stations, to use a separate dynamo for each pair of feeders, and to continually vary its output to suit the demand. It is preferable to use one or more dynamos connected to a pair of 'omnibus' bars, from which the whole of the feeders radiate. The potential difference between these bars may be kept equal to the maximum required, and the regulation effected by inserting resistance or counter electro-motive force in the respective feeder circuits. The insertion of resistance coils, however, while it is effectual and convenient, is wasteful. A more economical plan, for moderate loads, is to introduce a few secondary cells in each feeder in such a manner that they oppose the feeding current. The effect is simply to oppose a counter E.M.F. to the dynamo (since the cells have practically no resistance), but the potential difference is varied by the rather large steps of two volts at a time.

The advantage of using a number of machines in parallel instead of one large machine to supply the omnibus bars, is that a dynamo may be switched out and stopped when the demand for current falls. When the feeders vary considerably in length, it may be advisable to divide them into two or even more groups, according to their resistances, and supply the longer ones from a pair of bars maintained at a proportionately higher pressure than the similar bars supplying the shorter feeders.

In some instances subsidiary machines, termed 'boosters,' are employed to maintain the pressure on the feeders or at certain points in the network. A booster is really a motor-generator—that is to say, it consists of two parts, viz. a dynamo to give out a low voltage, and a motor which drives the dynamo, and which may itself be driven off the omnibus bars, so that in this case the bars are maintained at the normal voltage, and the extra volts are supplied by the booster, which may be placed either at the generating station or in a sub-station. As an illustration, we may take an arrangement frequently used in traction installations, where the variations in pressure, unless compensated for, are likely to be considerable, and where on account of the sudden changes in the load it is necessary that the boosters should be self-regulating. We will assume that it is required to maintain a pressure of 500 volts on the car-motors, then the main generators may be, say, three in number, and preferably compound-wound machines, over-compounded to give a pressure of 500 volts at no load, and 550 volts at full load. The three machines would be joined in parallel to the omnibus bars, and would be able to respond generally to an increase in the total load, but would not be able to keep up the required pressure on any one feeder circuit which might for the moment be overloaded. Even if they could do this, the result would be to apply an excessive voltage to the feeders which were not overloaded. The function of a booster set is to produce the required effect. The dynamo part of the booster should be joined directly in one of the feeder circuits, and the motor driving it should be a shunt machine connected directly across the mains, and therefore driven at a constant speed. The winding of the generator field-magnet should be such that the machine gives the maximum additional E.M.F. required, say 20 volts, when the current in the feeder is at its maximum value. This pressure of 20 volts will then be added to that particular feeder just when the load is at its maximum, and the machine should be approximately self-regulating, so that the number of volts added is proportional to the current passing through it, and therefore also proportional to the load on the feeder circuit.

Turning now to the methods of supporting, protecting, and insulating the conductors for lighting circuits we immediately

observe that they naturally divide themselves into two classes, viz. overhead and underground.

The overhead system has the advantage of cheapness in construction, and it affords great facilities for inspection and repair, and for subsequent extensions. It is therefore employed where the local conditions permit it, where the current employed is not so heavy as to require a very massive conductor, and where the potential difference is not excessively high. The system has, however, the disadvantage that the insulation is liable to considerable variation with weather changes. This can to a great extent be prevented by good construction and the employment of properly designed 'insulators.' A series circuit lends itself readily to the employment of overhead mains, since the current is in such cases constant, and rarely exceeds 10 amperes. A very small wire would be sufficient to carry such a current, but the size is really determined more by mechanical than electrical necessities. For example, a wire of No. 12 S.W.G. would carry a 10-ampere current with safety, but a No. 8 or even a heavier wire is actually used to give the necessary strength. All overhead bare conductors must be of hard-drawn copper in order to obtain the requisite mechanical strength. Ordinary pure copper is comparatively soft, and in a span of any considerable length cannot sustain its own weight; while in a gale the wind pressure enormously increases the stress upon the wire. It is now possible to obtain pure copper wire having a breaking weight of from 28 to 30 tons per square inch; the high tenacity is obtained solely by the molecular arrangement given to the particles during the process of drawing, and if the copper is really pure, the increase in resistance due to the hardening should barely exceed 2 per cent. The wire should be subjected to severe tests before it is accepted for erection. In addition to tests for tensile strength, uniformity, and freedom from flaws, &c., its ductility should be proved. It should be capable of being wrapped in six turns round wire of its own diameter, unwrapped, and again wrapped in six turns round wire of its own diameter in the same direction as the first wrapping, without breaking; and should also be capable of bearing a number of twists without breaking. The twist-test should be made by gripping the wire between two vices, one of which should be made

to revolve at a speed not exceeding one revolution per second. The twists thus given to the wire can be counted by means of an ink mark made along the wire before twisting, which forms a spiral round the wire as a consequence of the torsion. The number of twists is of course determined by the number of convolutions in the ink spiral between the vices. The following table refers to a few wires which are available for overhead work.

Weight per statute mile	Approximate equivalent diameter	Minimum breaking strain	Minimum number of twists		Resistance per mile at 60° Fahr.
lbs.	inches	lbs.			ohms
800	0·2237	2400	In 6 inches	15	1·098
600	0·1937	1800		20	1·465
400	0·1582	1250		25	2·197
300	0·1370	950		30	2·929
200	0·1119	650	In 3 inches	20	4·394
150	0·0969	490		25	5·858
100	0·0791	330		30	8·787

Bare conductors are supported on insulators which are in turn supported by poles either of iron or wood, according to local circumstances.

Insulators can be made from a variety of substances, but for climatic and other cogent reasons, white glazed porcelain is the best and is most frequently employed. The chief requirements are hardness, smoothness, and imperviousness to moisture, and lacking either of these, the insulator is practically useless. It should be hard in order to resist abrasion by the wire; it should be smooth, to prevent the accumulation of dust and dirt, to facilitate cleansing by rain, and to avoid the unnecessary wearing away of the conductor; and it should be impervious to moisture, in order that the rain should fall off instead of entering the pores of the substance and reducing, more or less permanently, its insulating properties.

Porcelain varies very considerably both in its constitution and in its manufacture. Some kinds are almost spongy, and as the glaze covers the insulators there is no possible means of testing, except by breaking them. The glaze often cracks after

a few months' use, or it may even be chipped by careless handling before the insulator is finally fixed in position, and then, if the interior is at all porous, it absorbs moisture, and so loses its insulating properties. When perfect, it is undoubtedly the best insulator available, although for tramway purposes a special material known as ambroine is generally used.

It must further be pointed out that the insulator should be sufficiently strong to withstand the maximum stress likely to be imposed upon it by the wire. When all is quiet the insulator has simply to bear the weight of half the span of wire on either side of it, but when there is much wind the strain is increased considerably by the swaying of the wire.

FIG. 371

In the case of a sound insulator, practically all the leakage takes place over the surface; and in order to make the path taken by the leakage current as difficult as possible, it is necessary to so design the insulator that that path shall have the maximum length, with the minimum area of surface between the wire and the steel bolt or spindle supporting it.

Considering the fact that the E.M.F. in an electric lighting or power circuit is comparatively high, it is pre-eminently essential that the insulation should be of the best; parsimony in this respect is very likely to prove but the forerunner of disaster. When the line is straight, so that normally there is no lateral strain, and the conductor is not more than a quarter of an inch thick, the porcelain insulator illustrated in fig. 371 is suitable. This insulator consists of a double 'cup' manufactured in one piece; the inner cup is shielded from rain by the outer one, and the length of the surface between the conductor and the supporting bolt is considerable. The peculiarity about it is that it is provided with an open coarse screw-thread by means of which it is screwed on to the bolt, which in its turn is permanently fixed to the arm or bracket on the pole. An indiarubber washer placed above the shoulder *a* at the bottom of the thread on the bolt, allows the insulator to be screwed on tight without involving

a risk of splitting it or stripping its thread. The principal advantage pertaining to the use of a screw bolt is that, in the event of fracture, the insulator itself can be replaced without necessitating the removal of the bolt. The conductor should be laid in the groove of the insulator and securely bound in position with soft thin wire of the same material as the conductor itself. Hard wire is not suitable for binding wire, as its springiness prevents its remaining exactly in the position in which it is placed, tight against the main wire. Experience has also shown that it is advantageous to wind a length of copper tape over the line wire before the binder is wound on.

When an insulated aerial conductor is used, as is sometimes the case for lighting and other similar purposes, it cannot be attached to the insulators direct, because the friction which is always at work would speedily cause the abrasion of the insulating material, and that at the very point where complete insulation is sought—viz. at the insulator itself. There is also the further difficulty that an ordinary covered cable with an annealed conductor has not sufficient tensile strength to enable it to support its own weight, without stretching, in a span of any considerable length. In such cases a steel wire or rope is secured to the insulators, and from this the cable is supported by means of a number of raw hide suspenders at intervals of a few feet.

One of the most important details in connection with the running of electrical conductors is that of jointing. The chief features which should pertain to a well-made joint are, that the electrical continuity should be fully maintained; that its mechanical strength should be at least equal to that of the conductor itself; that no free ends should be left on the finished joint; that it should be durable both electrically and mechanically; that it should be as compact as possible, and that with a covered wire the insulating coating should be made continuous and as uniform as possible.

For bare solid conductors up to a quarter of an inch or so in diameter there is no better joint than that known as the 'Britannia.' Fig. 372 illustrates a joint of this kind. The ends of the two hard-drawn conductors are carefully cleaned and laid side by side for a distance of about three inches. The binding

wire is then wound tightly over them, commencing perferably at the middle of the joint, and working towards each end in turn, a few convolutions being wound over the single wire at each end of the joint. The joint is finished by carefully and completely soldering it into one mass, care being taken to avoid over-heating it. If properly made, such a joint is stronger than the conductor itself; in most cases, however, it is found that the conductor on each side of the joint is slightly weakened by being heated during the process of soldering, and a break will generally take place at one of these points rather than in the joint itself. In jointing the larger sizes of solid wires it is frequently the practice to place a short length of thin tinned wire between the two conductors on each side of the joint so as to facilitate the running of the solder and the solidification of the joint.

FIG. 372

The method of jointing a covered stranded conductor is simple. Supposing it to be a 7-wire strand; the insulating covering is removed from each end for a distance of a few inches, care being taken to avoid nicking the copper or scraping away the tin. All the separate wires are then opened out, and the centre wire on each of the ends to be joined is cut off short. The two sets of wire are next brought end to end, and laced together, just as would happen if the two hands were placed palm to palm, and the fingers of one hand placed between those of the other. This being done, the protruding ends of each conductor are wrapped closely round the other, the two wrappings being in opposite directions. The joint is then trimmed round with the pliers, and the whole well soldered together. The soldering is a more important matter than would at first sight appear, since the solder is relied upon to maintain the electrical continuity. Every care should therefore be taken that the conductor surfaces are thoroughly cleaned before making the joint, that they are not handled more

than is absolutely necessary, and it is advisable to employ only resin as a flux. The conductor-joint having been completed, the insulating covering is then made good. When the insulating material is indiarubber, pure rubber strips are tightly wound over the conductor in several layers, followed by a layer of prepared rubber tape, cemented together by a small quantity of indiarubber solution. To make the joint thoroughly reliable the covering should be vulcanised, which may be effected by immersion for about twenty minutes in a bath of sulphur gradually raised from just above its melting-point to a temperature of 154° C., and then for ten minutes in a bath of ozokerit, which is raised from 154° C. to 164° C. Whatever process may be employed, the vulcanising of a joint after wires or cables are laid in position is a difficult and inconvenient operation, and it is frequently ineffectively performed, while there is always the disadvantage that the rubber covering for a short distance on each side of the joint becomes over-vulcanised. Consequently joints are avoided as far as possible, and when absolutely necessary they are usually insulated in a more or less temporary manner, as indicated above, by means of pure or unvulcanised rubber strip and tape. When the conductor is to be placed in an inaccessible position, such as in a channel in a wall, or under the floor, a continuous length without joint should invariably be employed.

When the conductors are to be laid underground, the chief difficulty to be contended with is the provision of efficient and durable insulation. The simplest method is to support the bare conductor at intervals by suitable insulators, fixed in a suitable channel or culvert. The maximum permissible distance between the insulators depends either upon the rigidity of the conductor or upon the tension which it can withstand. Since every insulator is a point of leakage, it is obviously necessary that the number of these points should be reduced as far as possible.

Long experience with underground chambers and channels, such as are employed for many other purposes, has shown that it is impossible to prevent the accumulation of water within them; hence it is a necessity that the conduit be well drained, and good drainage should be supplemented by ample ventilation. Even were

a conduit to be made watertight, there would still be sufficient moisture caused by the condensation to oxidise the ironwork, and to make the surfaces of the insulators damp.

It will, however, be evident that were the pipe or channel containing the conductors filled with some good liquid insulating material, this accumulation of moisture with the attending disadvantages would be avoided; and prolonged experiments have been made with heavy petroleum, but the results have not justified its adoption, and the only effective method of insulating underground conductors is to cover the copper with some durable solid substance of high specific resistance, such as indiarubber, bitumen, or paper.

In all such cases it is essential not only to efficiently insulate the conductor, but also to protect the insulating covering from deterioration by exposure, and to protect the whole cable from mechanical injury. When these points are very carefully attended to, an installation with insulated underground cables for the mains is very reliable, and gives little or no trouble in maintenance. But carelessness in manufacture or laying, or the use of inferior materials, gives rise to troublesome and often very expensive repairs.

There is still a tendency towards false economy in this matter. A thin covering of the insulating material is placed over the conductor, and when new and absolutely perfect, the insulation may test higher than is actually essential in practice. But the slightest indentation or abrasion of the covering, such as may easily happen, and does happen, in handling during the process of laying, even if it does not quite expose the copper, leaves such a weak spot that the development of a 'fault' there becomes only a question of time. The insulating covering, of whatever material, should be of reasonable thickness, not so much for the purpose of obtaining an extremely high initial insulation-resistance, as to ensure its maintenance at a fairly good value.

Guttapercha must not be used. If not exposed to light and air, it is practically imperishable, but it quickly cracks and perishes if employed in a dry airy situation; the great objection to it is that it softens at a comparatively low temperature, and hence allows the conductor to become decentralised when heated by the

current. Generally speaking, indiarubber is the best material available for insulating purposes; but really good indiarubber is expensive, hence a large number of substitutes have been tried.

Bitumen is a good insulating material, but it softens at a low temperature, and even at normal temperatures it is so plastic that the weight of the conductor itself would cause it to sink through the coating. The processes employed by the Callender Bitumen Company overcome these objections. The material is vulcanised or treated with sulphur, with the result that, while retaining its high insulating properties, it becomes sufficiently rigid to hold the conductor permanently in position, even though the temperature be considerably raised. The conductor is usually of stranded copper wire, tinned to protect it from the sulphur. It is first coated with a sheath of the vulcanised bitumen, applied under heavy pressure in one solid layer to the required thickness. This sheathing is then covered with cotton tape treated with bitumen, the number of layers ranging from one to five; the cable is passed through a bath of hot compound after each serving of tape. The next process, for underground cables, is to apply a coating of jute yarn, and, after another passage through the bath, to cover it with hemp braid. Most of the cables are subjected to this treatment, the higher degrees of insulation being obtained by increasing the thickness of the dielectric—that is, of the vulcanised bitumen. For the smaller cables, such as are employed for indoor work, a layer of parchment tape is interposed between the conductor and the bitumen.

For extensive underground systems the cables are either drawn into a series of earthenware conduits or ducts, or are laid in troughs of wood or other suitable material, and then filled in solid with hot bitumen. In the solid system the cable is supported by tapes or wedges so that the bitumen can flow under and all round them. An iron cover or a layer of fine concrete is provided as a protection against picks and other similar sources of danger. It may be urged as an objection to this system that, the cables having been once laid, cannot in the event of a fault occurring be withdrawn; but, on the other hand, the system permits of such good work being put in that the chances of a breakdown can be made very remote.

Paper is now being very freely employed as an insulator for electric light and power cables. The conductor is wrapped with strips of specially prepared tough paper, Manila paper being generally selected for the purpose. This is impregnated with resin oil compound in order to fill up the pores of the paper, and prevent a further absorption of moisture. The impregnated paper used by the British Insulated and Helsby Cables Company has a breaking strain of not less than 9000 lb. per square inch cross-section. The paper-covered conductor is encased in a lead sheathing, and so long as this sheathing remains intact good results are obtained, but of course a pin-hole is quite enough to ruin the insulation of the cable. Sufficient experience has, however, now been obtained in the manufacture and laying of these cables to ensure satisfactory results, and as the specific inductive capacity of paper is much lower than that of india-rubber or of any other of the usual insulating materials, the cables are especially suitable for use with alternating currents.

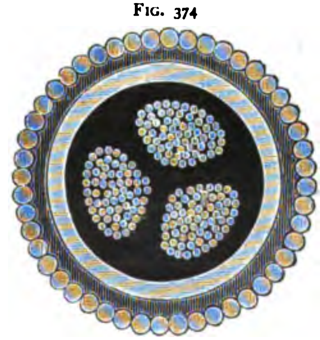
Fig. 373

Main cables for alternating currents are generally made with both conductors placed concentrically inside one sheathing, as by this means the inductive effect on neighbouring telegraph, telephone, or other conductors is neutralised ; and further, by putting both conductors in one sheathing, the loss of power due to induced currents in the sheathing itself is avoided.

The conductors for a three-wire service are usually made up into a single cable, frequently in the concentric form. In other cases, more particularly for high-tension work, each of the three conductors consists of a strand of copper wires separately insulated. The former type is illustrated in fig. 373. It will be seen that the central conductor consists of a strand of round copper wires, while each of the two others consists of a single layer of copper strip. The resistances of the two inner conductors which form the two outers of a three-wire system are equal, but the resistance of the

outer layer is usually much higher. This outer conductor forms the middle or 'neutral' conductor in the system and is frequently earthed. The paper is wound on and the cable is then dried at a temperature not exceeding 275° F., after which it is placed in the impregnating tank at a temperature of 250° F. It is then transferred to the hydraulic lead press and sheathed. The other type of three-core cable is illustrated in fig. 374, in which the three conductors are separately served with paper insulation, and the whole are then enclosed in a single lead sheath. When a cable is to be drawn into a smooth pipe or conduit, no further protection is, as a rule, required, but in some cases the cable is laid direct on the ground or in situations where mechanical protection is necessary. This is afforded by coating the lead with a layer of jute yarn treated with compound and then armoured, as shown in fig. 374, with a layer of galvanised iron wire. In cases where no provision against stretching is required, or where tensile strength is not an essential feature, an armouring consisting of two layers of steel tape is provided, and is, if anything, more effective than the wire.

FIG. 374



Wires inside a building must be efficiently protected to avoid damage or accident, as well as to maintain the insulation. It is usual to run the wires either in iron tubing or along parallel grooves in a wood casing. When in the latter case it is necessary for one wire to cross another, a slip of wood is interposed. The casing can be made in a variety of forms, and if necessary can match the moulding or cornice, but the employment of iron barrel or tubing for indoor wiring is much to be preferred and is rapidly extending; it is a method which ensures immunity from damage, and offers the great advantage that it may be buried in plaster or brickwork without the risk of injury from nails, &c., driven into the wall. Of course it is essential that the conductor should be absolutely free from joints inside the iron barrel. In

some quarters considerable importance is attached to the provision of an insulating lining in iron or steel tube work, but it is better to put the insulating material on the wire than on the tube. If the wire is well insulated, an insulating lining is unnecessary; if the wire is poorly insulated, the sooner it breaks down, and the more decidedly it breaks down, the better. The tubing should be metallically connected throughout the system and should always be connected to earth.

Indiarubber covered with braided hemp or cotton forms about the best material for insulation for indoor work.

Coming now to the question of electric-traction circuits, it may be said that there are three distinct methods of running the conductor. In the first place it may be carried on insulators in a conduit constructed between the rails, the collector or trailer which makes the necessary sliding contact passing down through a slot in the top of the conduit. This method has distinct advantages, but as the slot must necessarily be narrow, it is a difficult matter to maintain the insulation of the trailer from the edges of the slot, and, further, the conduit is liable to be choked up with rubbish, water, snow, &c. Consequently, in order to make the system effective, the initial outlay, as well as the cost of maintenance, becomes almost prohibitive. It is manifest also that it is extremely difficult to arrange satisfactory crossings for the lines, and further, that the permissible potential is limited.

The second method, in which a third rail insulated throughout its entire length is run between the two car-wheel rails and at a little higher level, possesses none of the above disadvantages, but of course it cannot be made use of in a street or where any other traffic is required to pass over the road. It is the system usually adopted on an overhead or an underground railway, and a pressure of 500 or 600 volts may safely be employed when, as is the case in England, only authorised persons have access to the line. The rails under this system are usually employed for the return lead, but great care has to be taken in electrically binding the several lengths of rail together. The outer or running rails should be effectively 'earthed.' The middle or 'live' rail must be higher than the running rails, otherwise the trailer or contact-maker hanging from the motor truck might foul the running rails

at a crossing, and there would also be some risk of putting the live rail direct to earth.

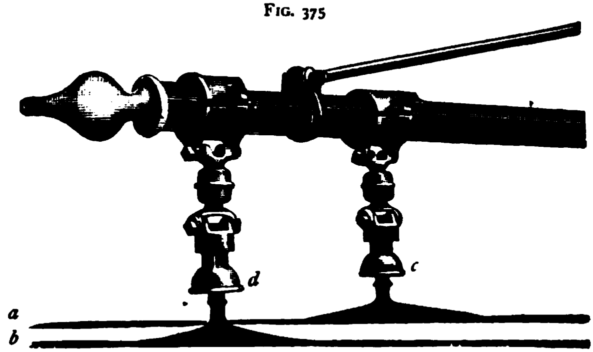
For ordinary street tramway work, and quite as much so for railway work, the ideal system from an engineering point of view is without doubt that in which an overhead conductor is employed. This conductor usually consists of a hard-drawn copper wire usually of round section, but sometimes wires of other sections are employed. The following table gives particulars of the round wires generally adopted.

Gauge	Standard diameter	Standard weight per mile	Resistance per mile in ohms at 60° F.	Breaking strain			
				Lb.		Tons per square inch	
	in.	lb.		Min.	Max.	Min.	Max.
0	·324	1678	·5132	4435	4620	24	25
00	·348	1936	·4448	4900	5320	23	25
000	·372	2212	·3893	5600	6100	23	25
0000	·400	2557	·3367	6330	6890	22·5	24·5

The trolley wire is suspended at frequent points throughout its length from specially designed insulators, which in their turn are supported either from horizontal arms projecting at right angles from poles fixed at the side or middle of the road, or from 'span-wires.' These span-wires usually consist of stranded galvanised iron or steel wire rope supported between two poles, one on each side of the road. In fig. 375 is illustrated the method of supporting the conductors from a stout tubular steel arm, which is attached to and supported by an iron or steel standard on the pavement or on the side of the road. The hanger illustrated is made by Messrs. Dick, Kerr & Co. The two trolley wires *a* and *b*, one for the up line, and the other for the down line, are secured to the bolts which are cemented in the insulator cups *c* and *d*. These insulators are secured to flexible couplings which are supported by clamps attached to the bracket, an insulating sleeve being usually placed between the clamp and the bracket. These sleeves are, however, of little service, as after a short time they become covered with dust, or in town districts with soot, and then, especially in damp weather, the resistance between the clamp and

the bracket is very low, if not altogether negligible. Where space permits, the neatest arrangement is to fix tubular iron or steel poles in the middle of the road between the up and down lines, an arm projecting from each side to support the insulators in such a way that the conductors are suspended immediately over the track. Connection is made between the conductor and the car by means of a light arm or pole either of wood or tubular steel, which is carried on the roof of the car, and, by means of a flexible joint and a number of suitably disposed spiral springs, is allowed sufficient freedom of motion to readily follow the conductor. The upper end of the arm carries a grooved wheel of brass or gun-metal, known as the trolley-wheel, and the conductor lies in the

FIG. 375



deep groove of the wheel, which is pressed upwards by the springs at the base of the pole with sufficient force to make good contact. There are many modifications of this arrangement (sometimes, indeed, a sliding shoe is employed instead of the wheel), but good results are obtained with a gunmetal wheel insulated from the top of the arm, the current being collected from the wheel by means of a brush or flat spring pressing against it, and carried down through the hollow arm by a heavily insulated wire to the controlling switch. The arm stands backward at an angle of rather less than 45°, and a cord is attached to its free end, by means of which it can be pulled down and the trolley-wheel replaced in position should it at any time leave the conductor.

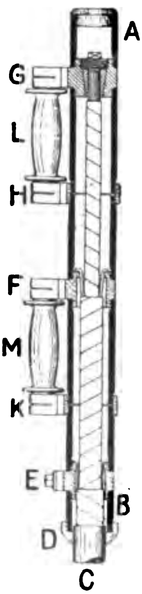
Of course extremely careful construction and frequent inspection in the case of the overhead conductors are essential, in order to avoid any accident to life or property, which might result from one or more of the conductors giving way either through wear or failure of the supports. The pressure is usually about 500 volts, and although a continuous current is employed, such a pressure with a large generating-station plant behind it must always be very dangerous in the event of a 'trolley wire' falling near to or on the ground. There is also one other danger consequent upon the existence of a large number of overhead telephone and telegraph wires. These wires are led into private houses, offices, warehouses, &c.; they are usually of comparatively thin wires and frequently the spans are long. Were such wires to break and fall across the trolley wires, the full pressure of the generator would, until the thinner wire melted, be conveyed to the building in which the telephone or telegraph wire terminates, and serious damage might easily ensue. Much care has been bestowed upon the methods to be adopted in order to avoid accidents of this character, and as the telephone and telegraph wires are necessarily run at a higher level than the trolley wires, the practice has been generally adopted of running steel 'guard wires' above and parallel to the trolley wires. These guard wires should be earth-connected so that, should an accident of the nature referred to occur, and should the telephone wire coil round into contact with the trolley wire, the generator shall be 'put to earth' rather than be joined electrically to the building served by the broken wire.

The earthing of the trolley wire through the guard wire also has the effect of sending a too heavy current from the generator, and a magnetic cut-out or a safety-fuse should be placed in the circuit, so that the trolley wire, or a particular section of it, is disconnected. This, of course, results in a temporary breakdown of the tramway system.

It should be manifest that when a number of cars are connected in parallel between the overhead conductor and earth, the current sent out from the generating station may reach a high value, and if the overhead conductor alone were relied upon to transmit the whole of the current thus sent out, the fall of potential therein

would be considerable, and the pressure applied to the motor terminals at the far end of the line would be much less than that at the near end. Even if, as is sometimes the case, the generators are compound-wound machines and over-compounded in order that the E.M.F. developed may rise above the normal when a heavy current is being sent out, there must still be the same difference in the pressure at the extreme ends of the line. The best way of overcoming this difficulty is to employ a system of feeders—that is to say, to run a number of supplementary conductors from the generating station, and connected to the overhead conductor at various points along the line. These feeders are usually run underground, and when they are made use of, not only can the pressure throughout the line be maintained at a more uniform value, but it then becomes possible to divide the line into sections, which can be electrically separated from each other by means of suitable switches, so that a breakdown in any one section means a complete stoppage in that section only. The feeders are usually connected to pillars fixed on the pavement, and from these pillars the wires are led up the poles to the adjacent sections of the line. A sectional view of one 'unit' of one of these pillars, of the Prescot pattern, is illustrated in fig. 376. A B is an insulating tube fitted for a three-wire concentric cable C, similar to the one illustrated in fig. 373. The aperture where the cable enters is closed by the gland D. The lead is removed from the cable above this point, and the outer or neutral conductor is connected to the 'bus-bar' terminal E. The second or middle conductor of the cable is similarly connected to the negative terminal F, and beyond this point there is only the inner conductor (with its insulation), this conductor being effectively connected to the positive terminal G. The terminals H and K are connected to the positive and negative bus-bars respectively, and the circuits to those bars are completed by inserting the safety-fuse holders, L and M. From the

FIG. 376



bus-bars distributing cables can be led (each through a separate safety-fuse) to any required portion of the system. It is customary to provide a feeder for every 3200 yards of track, but on heavily worked systems the distance is reduced to 2200 yards or even less. The dimensions of the feeders themselves are based on a fall of potential which under normal conditions ranges from 5 to 7½ of the applied voltage.

It will be remembered that in describing the London system it was mentioned that a number of sub-stations are provided which are supplied with current at a high potential, to be reduced at the sub-stations to the working pressure and distributed to the several pillars along the routes. It is laid down that on such heavy systems it is not economical to run the feeders direct from the generating station for a greater radius than about four miles.

It has been specified by the Board of Trade that the maximum power supplied by a feeder shall not exceed 300 kilowatts—that is to say, the current at a pressure of 500 volts must not exceed 600 amperes. It has also been specified that fall of potential in the rails shall not exceed 7 volts. The use of the rails for an earth return opens up some important considerations, for, as a little reflection will make evident, there is considerable risk of gas, water, and other pipes being brought into the circuit, with the result that these pipes after a time become injured or even destroyed by electrolysis—that is to say, by an effect similar to that which takes place on one of two metal plates immersed in a conducting solution when a current is passed through them. For this reason every effort is made to afford a return path of the lowest possible resistance through the rails. The chief difficulty occurs at the joints in the rails, on account of the resistance due to rust, &c., at the points of contact between the rails, bolts, and fishplates. The difficulty can, however, to a certain extent, be overcome by the use of suitable 'bonds' or supplementary connectors between adjacent lengths. An effective bond consists of a copper rod with its ends swelled out and bent at right angles to the length of the rod. These ends are driven into holes drilled through the webs of the rails; a hole is drilled into the end which projects through the web, and

by driving a steel plug into this hole the end of the bond is expanded and good connection with the rail is thereby ensured.

Another method of overcoming the difficulty of joints in the rails is to electrically 'weld' the ends of the sections of the rails together and thus make one continuous line. This has the advantage that an extremely good electrical connection is maintained throughout the whole length of the rail, and moreover the cars run much more smoothly on a track in which the rail joints are welded. The method has been somewhat extensively tried, particularly in America, but it has been found that since the sections of the line are not free to expand and contract with varying temperatures, the metal is subjected to strains of such magnitude that they sometimes lead to rupture. The process of electrical welding was explained in Chapter XIII.

We have described in the early chapters certain pieces of measuring apparatus, but there are a few internal fittings to which some attention must be paid. Perhaps the most important of these is the switch, a piece of apparatus which is in constant use and for a variety of purposes, but chiefly to form a ready and expeditious means of making and breaking a circuit. In order that a switch may be capable of efficiently performing its functions, its metallic parts must be sufficiently massive to carry the required current without heating or offering any appreciable resistance; the contact surfaces must for similar reasons be of ample area; the moving contact piece must press firmly on to the fixed one; and simple striking contacts must give place to rubbing contacts, to avoid partial insulation through accumulation of dust and metallic-oxide films. The circuit should not be completed through the spindle upon which the arm or lever travels, as dirt and dust are liable to accumulate at the bearing surfaces, and in time impair the efficiency of the switch; and generally speaking it is preferable to so design the switch that the end of the lever shall be forced between two contact blocks and simply join them together.

The switch should be so constructed that there is the minimum abrasion and wearing compatible with good and certain contact, and such parts as do wear away should be easily adjustable or cheaply renewable, so as to permit the re-establishment of good

contact. In all cases, but more especially for currents of high voltage, the lever should be provided with a handle of insulating material; and the breaking distance through which the arm travels should be sufficient to prevent a spark following the retreating arm and setting up an arc. When contact is broken, the current (especially if it is of a high electro-motive force, or if the circuit contains any apparatus having considerable self-induction) sparks across a portion at least of the air space in the effort to continue its course, and thereby volatilises a portion of the metal surfaces. If such an arc has been once established its maintenance is not a matter of great difficulty; and it is evident that such an arc is quite competent to start a serious fire, besides in any case damaging the switch contacts. It is advisable to provide a snap-action, so that the lever is set decidedly either on or off the fixed contact, the spring being so arranged that the lever is jerked quite away when it is turned almost out of contact. The terminals should never be so placed that, in turning the handle, there is any chance of the instrument being short-circuited by the operator's hand. The base of the instrument should be of some good insulating material, not liable to warping or appreciable expansion or contraction. Wood, therefore, should never be used. What is required is a material which is non-inflammable, a good insulator, does not readily condense moisture, nor facilitate the accumulation of dust and dirt. Slate is a good material if free from impurities such as mineral streaks or veins; glazed porcelain condenses moisture freely and is brittle. The conductors, especially those of the stranded type, should not be clamped under a nut or washer, but soldered into a socket or thimble which can be bolted on to the switch-block.

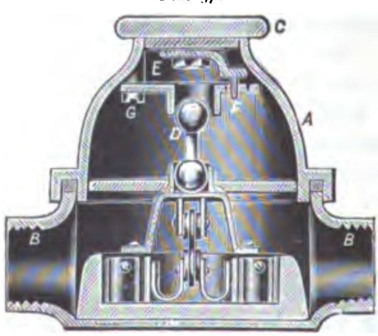
'Double-pole' switches are switches which complete or disconnect both the positive and negative conductors simultaneously. They usually consist of a pair of 'single-pole' switches, linked together by an insulating bar, both levers being actuated by a common handle.

A switch of some kind is required in connection with every incandescent lamp or group of lamps, and of this class there is a vast number in use, the best example of which is the well-known Tumler type of switch.

In many cases it is essential that the whole of the wiring and switches shall be protected by watertight covers. So far as the wiring is concerned, a lead-covered cable will secure this object, but the lead is easily injured, and it is preferable to enclose the conductors, even when they are lead covered, in a substantial iron or solid drawn steel tube. It is not quite so easy to enclose such items as switches and wall plugs, but very simple and ingenious contrivances have been devised by Messrs. Pinching & Walton, and are used extensively by the Admiralty and other bodies. A view of the switch and cover is given in fig. 377, and a section in fig. 378. The cover or box is usually of iron, and is made in two parts, A B, which are screwed together as shown in fig. 377, an indiarubber ring being clamped between them and making an effective watertight joint. A brass disc, C, with a milled edge, is truly faced with another disc which is fixed underneath it. The disc C carries a short vertical spindle which passes through the lower plate and through a substantial indiarubber disc, on the lower face of which is a metal washer; under this washer is the bent lever E, the whole combination being securely clamped together by means of a nut, and providing a perfectly watertight cover. The free end of the lever E carries a short pin F, which passes

FIG. 377

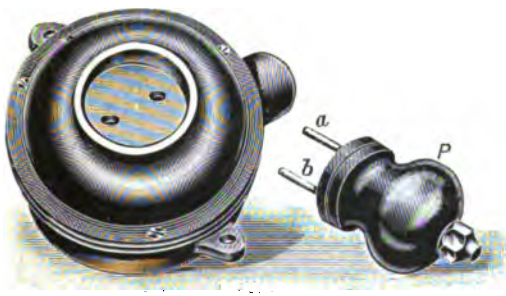
FIG. 378



through and engages with a lower lever which turns on the screw G. The latter lever is provided with a cup or short tube, which controls the position of D, the knob of the Tumler switch fitted in the lower portion of the box. It will thus be seen that if C be rotated, the pin F will turn with it, and will move the lower lever, so as to actuate the switch either to the 'on' or to the 'off' position, according to the direction in which it is rotated.

Another valuable production by Messrs. Pinching & Walton. is the watertight wall-socket, illustrated in figs. 379 and 380. The student is probably aware that a wall-socket is a device by means of which a lamp (or small motor) provided with a portable plug, P (fig. 379), can be readily connected to or disconnected from the

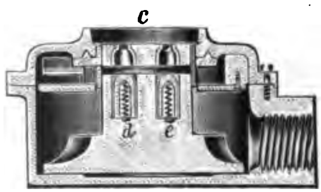
FIG. 379



circuit. When an ordinary wall-socket is used the wires from the lamp are led into the plug and connected to the metal pins such as those (*a b*) which project from the plug P. On the face of the socket are two holes under which in the ordinary pattern there are a pair of thimbles connected to the positive and negative mains, so that when the pins are inserted in these thimbles the current is conveyed to the lamp. In the case, however, of this particular socket there is the additional device for rendering it watertight, spark-proof, and automatically self-closing. The socket is encased in a stout iron box, consisting of an upper and a lower part screwed together, and the joint made watertight. Projecting from the bottom is a cylindrical mass of insulating material in which are embedded two spiral springs, *d*, *e* (fig. 380), each provided

with a comparatively long and loose-fitting cap or thimble, after the manner of the bayonet lampholder, fig. 344. These are shown to be pressing against the rotatable cover *c*. On a diameter at right angles with the diameter passing through the springs, two substantial metal socket pieces are embedded in the insulating cylindrical block. These socket pieces are the same distance apart as are the caps and springs, and are, moreover, connected to the positive and negative conductors respectively. In fig. 379 the cover is in its position of rest or inaction, and the two caps are shown to have been forced by the springs through the holes in the cover so as to be about flush with its outer surface. When the pins of the plug are pressed into the holes, the caps are driven down just below the level of the lower surface of *c*. Assuming the plug to be then rotated through an angle of 90°, the pins will fall into the socket pieces already mentioned and complete the circuit. Attached to the cover *c* is one end of a coiled stiff wire spring, the other end of which is secured to the iron box. In turning the plug and cover through the angle of 90° the wire spring is coiled up, and is therefore under tension.

FIG. 380



When it is desired to break the circuit, and the plug is withdrawn, the wire spring draws *c* smartly round so as to completely cover the socket pieces and allow the caps or thimbles to spring out, and practically fill up the holes in *c*.

Highly important as switches undoubtedly are, cut-outs cannot be said to be much less so. The function of a cut-out is primarily to prevent damage being done to the apparatus, the leads, or the building in which they are placed, by means of an unduly strong current; and the way in which it affords this protection is by automatically disconnecting the circuit when the current from some cause, accidental or otherwise, exceeds a certain pre-determined limit.

There may be said to be two species of cut-outs—(*a*) those actuated by an electro-magnet, and (*b*) those carrying a piece of wire or foil which melts or fuses when the current exceeds a definite strength.

A magnetic cut-out consists essentially of a coil of wire placed in the main circuit and provided with a movable core, or armature, to which is attached a strip of metal also forming a part of the main circuit. When the current rises above the prescribed strength, the coil attracts its core or armature with sufficient force to draw away the strip and break the main circuit. But it is necessary for the contact made by the strip with the ends of the main circuit to be very good and also frictionless, otherwise the pull required to break contact would be liable to vary. In one type of instrument the two ends of the main circuit terminate in cups which are partly filled with mercury, after the manner illustrated in fig. 311. The contact is reliable, but there is a chance of serious sparking occurring at the mercury surface when the contact is broken with a heavy current, or at a high E.M.F., especially if any large electro-magnet having considerable self-induction is included in the circuit. When there is any risk of serious sparking it is advisable to cover the mercury with oil (which is an insulator) in order to reduce the possibility of damage being done. The advantages of such a cut-out are, that it can be readily adjusted to act with certainty with any given current, either by varying the tension of an antagonistic spring, or by altering the centre of gravity of the moving piece. It can also be arranged to automatically restore the connection when the current falls again to a safe value. This latter arrangement is not as a rule adopted, but the apparatus can be immediately restored to its normal state by hand when the cause of the abnormal rise in the current has been discovered and removed. It is manifest that the resistance of the apparatus must be kept extremely low to avoid serious loss of power. It requires a certain amount of attention, and is expensive compared with the type next to be considered.

A safety fuse can be constructed so as to offer very little resistance, and therefore to absorb but little power. It must of course offer some resistance, since it is owing to the heat developed by the current in overcoming this resistance that the fuse is melted. Obviously a fuse made of a metal which has a low melting-point requires comparatively little electrical energy to raise it to a state of fusion; and hence a fuse composed of such a

metal may be made of lower resistance, and so absorb less power, than if a metal with a high melting-point (such as platinum, 2000° C.) were employed. In fact, with a well-designed fuse the chief cause of loss of power is likely to be in the careless connection of its extremities to the terminals.

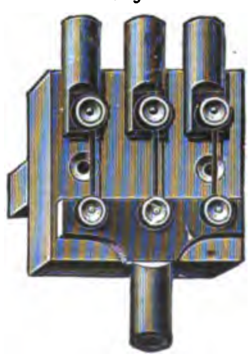
Such a cut-out has no working parts likely to get out of order or to need any attention; it is inexpensive, and, if properly designed, can be relied upon to act when the current reaches any particular strength, or at any rate within about 5 per cent. of it. The fuse must be designed so as to break promptly and certainly, and it should not for ordinary purposes be of a material which might get red-hot before it melted, otherwise the danger from fire becomes serious. The lower the temperature at which the metal employed melts, the less is the danger thus incurred. It must not be forgotten that good conductors of electricity are also good conductors of heat, and that therefore the terminal screws to which the fuse is attached tend to conduct the heat away as well as to dissipate it by radiation. This fact necessitates the fuse being made rather longer than would otherwise be required; and while the terminals must be sufficiently massive to allow good and reliable connection, they should not be unnecessarily so.

It is almost superfluous to add that the metal employed should be durable, and not subject to change from any cause such as oxidation. Platinum fulfils this condition admirably, and yet it is unsuitable for general work on account of the high temperature at which it melts. It is, in fact, easy to maintain it at a bright red heat for a considerable length of time. Tin, however, melts at 235° C.; it is very durable, only slightly oxidisable, and, taking all things into consideration, is the best metal for a fuse. There is a disadvantage peculiar to tin, viz. that its molecular structure alters in time, and permits it to carry much more than its standard current, and in many cases either platinoid or even copper is preferred.

The base on which the fuse is mounted should be incombustible, and is usually of slate or glazed porcelain. It should also be protected with an incombustible cover, preferably of porcelain or metal.

It is the best practice in any wiring scheme to interpose a fuse at the point where a branch wire is connected to a conductor of larger gauge, but the fuses should not be distributed in all sorts of out-of-the-way places, the better plan being to lead the mains or sub-mains to some convenient point and to lead the branch circuits from that point to the various parts of the installation. A simple illustration of such a system is given in fig. 381, where the main is joined to a metal strip from which three branch circuits are served, with a fuse in each branch. For large conductors a fuse should be inserted in both the positive and negative leads, but in small ones it is usually considered sufficient if a fuse is placed in one lead, say the positive, and the switch on the other. Where, however, a number of fuses are mounted on a single base for purposes of distribution, they should be so arranged that the molten metal from a ruptured fuse should not be able to fall upon a neighbouring fuse.

FIG. 381



For heavy current circuits several comparatively small fusible strips are frequently used, instead of employing a single massive strip, an arrangement which makes more certain the breaking of the fuses when the particular current strength is exceeded; but when the current is of high voltage it is essential that the fuse should be encased in an incombustible tube such as porcelain or brass. Sometimes the tube is filled with sand or other similar material in order to prevent the metallic particles being blown about when the fuse 'goes.' The Mordey fuse is of this type.

One possible objection to the use of a fuse is that when it does act under the influence of a too powerful current it is destroyed, breaks the circuit, and must be replaced before that circuit is again available. It will be evident that such cut-outs must be cheap, and placed in accessible situations. The number employed should be made as small as possible, for every one is a source of leakage, and may even be a source of danger. There is one case in which a fuse should never be used, and that is in the case of an

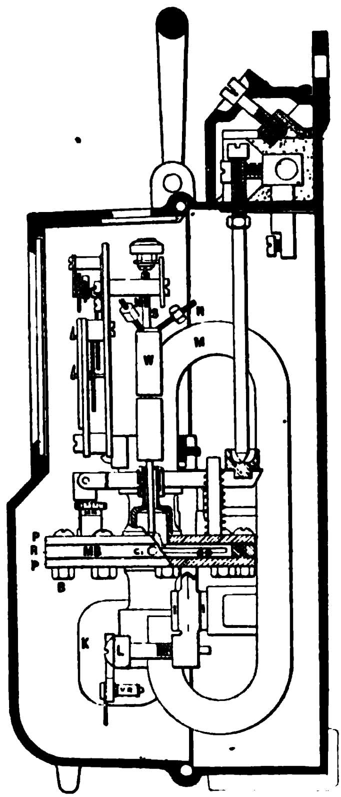
earthed conductor such as the 'outer' of a concentric cable. The danger is that an excessive voltage will cause the fuse to 'blow,' and when the fuse has blown, the outer may still be at a high potential. Cases have been known where such an arrangement has had fatal consequences.

In a previous chapter we have described certain instruments called ammeters, which are capable of indicating the number of amperes of current flowing through them at any particular moment, but which are unable to measure the actual quantity of electricity passed through them during any given period. In just the same way a thermometer indicates the temperature at any moment, but gives no idea of the quantity of heat actually developed or absorbed. In the commercial distribution of electricity it is essential that a 'meter' should be provided which is capable of measuring and, by some means, recording or registering the quantity of electricity supplied to any one consumer during, say, a month or three months. The unit quantity of electricity is the coulomb —that is, the amount transferred by a current of one ampere during one second; hence an instrument such as that referred to might aptly be called a coulomb-meter.

The coulomb is, however, too small to serve as a unit for working conditions. The next step is to employ as a unit the quantity of electricity transferred by a current, one ampere in strength, during one hour, this unit being known as the 'ampere-hour.' If, for example, a secondary cell were allowed to maintain a current of 15 amperes for 2½ hours, the *quantity* of electricity obtained from the cell during that time would be $15 \times 2{\cdot}5 = 37{\cdot}5$ ampere-hours, and the amount of electrical energy expended could be found by multiplying by the pressure in volts, the result being expressed as 'watt-hours.' But even this larger unit is somewhat small for the measurement of supply on an extensive scale, and a still larger unit, known as the Board of Trade unit, or kilowatt-hour, has taken its place. It is equal to that amount of electrical energy which is developed or absorbed by a current of 1000 amperes at a pressure of one volt duing one hour. It is therefore equal to 1000 ampere-volt-hours or 1000 watt-hours. This Board of Trade unit is, then, the unit by which the electricity supplied is measured and charged. In most cases

a certain piece of apparatus is introduced to measure the number of ampere-hours supplied to the consumer's lamps, and this quantity multiplied by the standard pressure in volts and divided by 1000 gives the number of Board of Trade units of energy which is indicated on the index and upon which the charge is based.

FIG. 382



The Ferranti continuous-current meter is illustrated in fig. 382, which is a side elevation of the instrument. It consists essentially of a horizontal disc floating in mercury between two pairs of magnet poles. The current to be measured enters at one point on the periphery of the disc, and leaves at the centre, so that a field of force is set up, and as a consequence the disc rotates, the number of revolutions being indicated by a series of light pinions which control the needles on the dial plates. The instrument is contained in an iron case divided vertically in two parts. The mercury is contained in a horizontal box or bath, MB, composed of two nickel-plated brass plates, P P, separated by a fibre ring, R, the internal surfaces of the plates being insulated from the mercury by means of sheets of presspahn. The plates and fibre are secured, so as to prevent the mercury escaping, by means of nine bolts, one of which is shown at B. The metal disc C D is platinum-plated and insulated by a coating of enamel, the edge and centre being left unplated, but amalgamated with mercury so that the current may enter and leave at definite points. The disc is carried

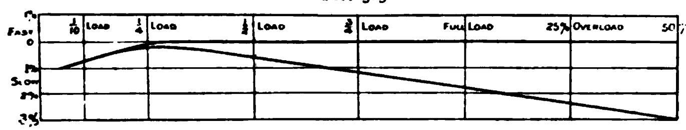
by the spindle S, which is supported by a cup-jewel. The spindle also carries a weight, W, which is adjusted so that the disc just sinks into the mercury, an arrangement which ensures the minimum friction between the spindle and the jewel. Three small nuts, N, are provided for adjusting the balance of the disc. One of the two permanent magnets is shown at M, and pole-pieces are secured to all the four poles, so as to form two vertical fields through the disc on opposite sides of the spindle. One terminal of the instrument is connected to the contact screw C, let into the fibre ring, whence the current is conveyed through the mercury to the edge of the disc, leaving the latter at the centre and passing out to another contact screw not shown in the figure. The path of the current through the disc is across the field set up by the pole-pieces of one of the permanent magnets (known as the driving poles), and the consequent repulsion of the two fields causes the disc to rotate, the driving force being proportional to the current. The motion sets up in the disc eddy currents due to both pairs of poles, which, acting on the flux from the poles, produce a retarding force on the disc proportional to the speed. If there were no fluid or other friction this would be the only retarding force acting on the disc. When the disc settles down to a uniform speed, the driving and retarding forces are equal, and as the former is proportional to the current, and the latter to the speed, it follows that the speed is proportional to the current.

As the speed increases the disc meets with another retarding force set up by mercury fluid friction, whence the meter would run slow at the higher loads. To overcome this, the current after passing through the bath is passed round a coil, K, wound round an iron bar, L, which is attached to the lower poles of the two magnets. The coil is so connected that when the current passes the magnetic flux produced increases the flux in the driving poles and decreases the flux in the retarding poles. Since both pairs of poles retard the motion of the disc, and since the flux in one is increased and decreased in the other by the same amount, it follows that this magnetic brake force is the same with or without the coil in action. But the driving force is increased at top loads, thus rectifying the effect of fluid friction. Fig. 383 shows two curves, one the percentage error with an uncompensated meter, and the other with a

compensated one, which latter curve shows that the accuracy between the full and $\frac{1}{10}$ load is well within the limits demanded in practice.

The voltage drop of a 10-ampere meter is about 0·06 volt, and the starting current is about 0·05 ampere. It is interesting to note that owing to the transverse position of the compensating coil, the constant of the meter is not appreciably affected by the passage of a short-circuit current through it. The instrument is adapted for loads ranging from 3 to 100 amperes, but for larger currents a shunted meter is used, the shunt taking the greater portion of the current. The student will, no doubt, have noticed that there are no brush or other rubbing contacts, and the accuracy over the whole range of the instrument from 50 per cent. overload to one-twentieth of full load is another decided advantage.

FIG. 383



Another good meter is the Aron Electricity Meter, illustrated in fig. 384. It is provided with the usual speed-counting index, which is actuated by the difference in the speed of rotation of two distinct sets of clockwork. Each set is furnished with a pendulum, both pendulums being adjusted to oscillate at exactly the same rate in the absence of any disturbing element. The bob of the pendulum shown on the left in the figure is an ordinary weight, but that of the right-hand pendulum is a permanent magnet. So long as both pendulums continue to oscillate at exactly the same rate, no movement of the indicating pointers takes place, but they begin to indicate directly the right-hand pendulum is accelerated. This acceleration is made to take place by means of a solenoid fixed underneath the magnet, and through which the main current passes. As the acceleration is proportional to the strength of the current, it is evident that the instrument can be so adjusted that the index will indicate in ampere-hours. To make this or any similar meter serve the purpose of an energy meter, it

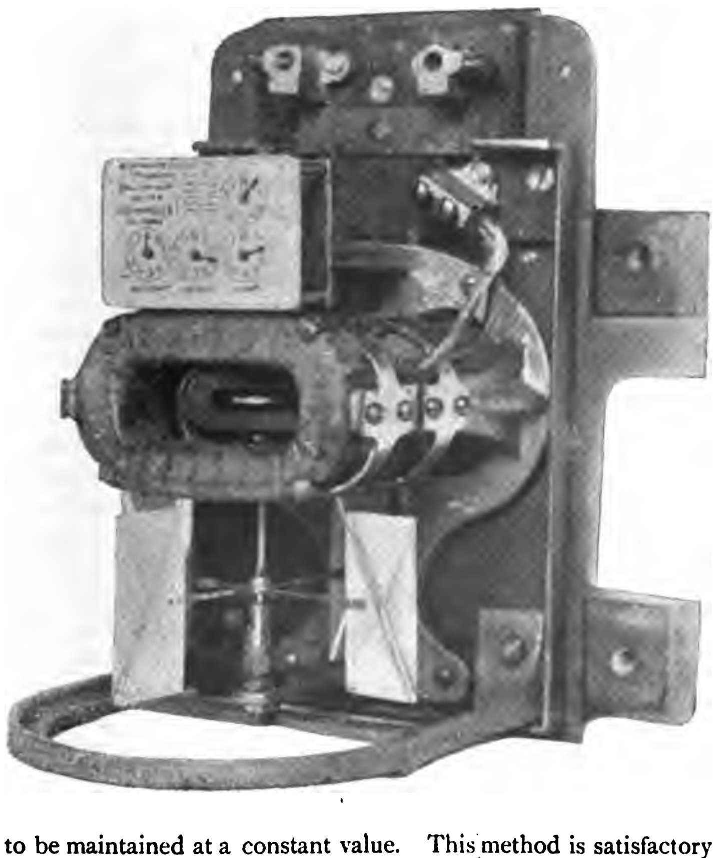
is necessary to multiply the ampere-hours by the standard pressure at which the current is supplied, and hence the accuracy of the

FIG. 384

result depends quite as much upon the constancy of the pressure as it does upon the accuracy of the instrument.

The measurement of the amount of energy supplied during a given time to a consumer on an alternating-current system may also be effected by measuring the quantity of current supplied during that time, and multiplying by the pressure which is assumed

FIG. 385

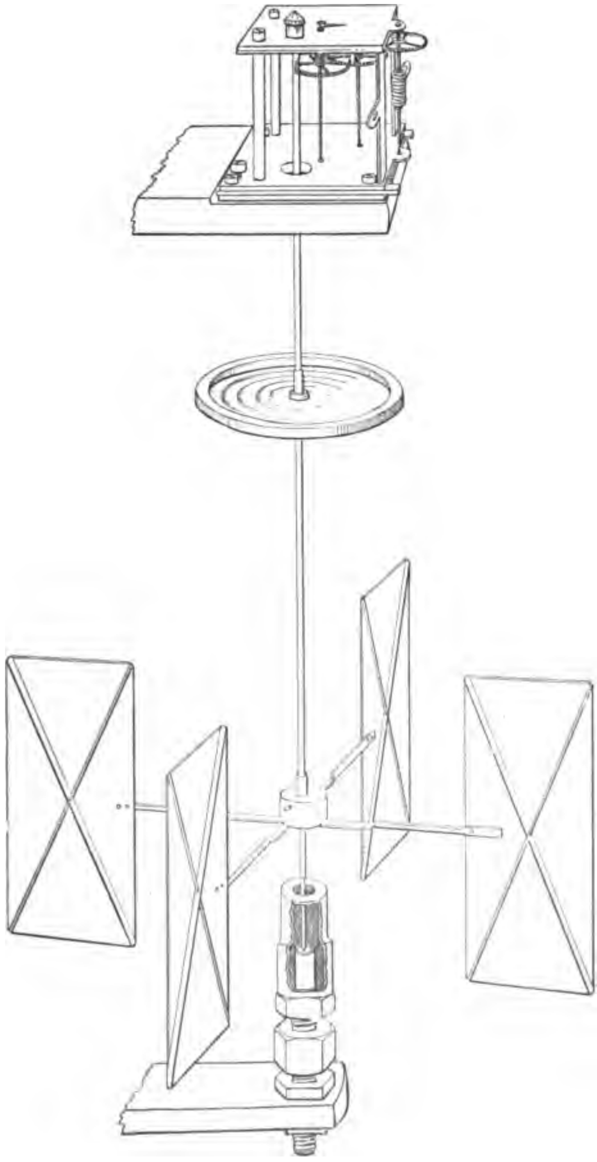


to be maintained at a constant value. This method is satisfactory (except that it does not take account of variations in pressure) provided only that the current is supplied to a non-inductive circuit such as that formed by a number of incandescent lamps

joined in parallel. It is evident, however, that it would be misleading if the circuit contained considerable self-induction, because in such a case the lag of current behind E.M.F. must also be taken into consideration. The Shallenberger Meter is an instrument which answers very well indeed when used on a circuit such as the secondary circuit of a transformer feeding a number of incandescent lamps. A general view of the instrument with its cover removed is given in fig. 385, the moving part and counting mechanism being shown in fig. 386. The moving or rotating part consists of a vertical steel spindle, which passes clear through a hole in the lower brass plate of the mechanism framework, and carries at its upper end a pinion gearing into the counting mechanism, the number of revolutions of the vertical spindle being indicated in the usual way by the four pointers shown in fig. 385. The main vertical spindle rotates at a rapid rate, and the first section of the train-work employed to reduce the speed is shown in fig. 386. This part is exceptionally well made in order to avoid friction, which would here introduce a great error on account of the high speed of rotation ; the spindles are vertical, as shown, and their lower ends rest on a polished glass surface. The remainder of the mechanism is somewhat coarser, the spindles being placed horizontally, and the motion is changed from a vertical to a horizontal plane by a screw and worm-wheel, the former of which can be seen in fig. 386. The bottom end of the main spindle is of hardened steel, rounded, and it rests on a cup-shaped polished jewel support, so that it rotates with a very small amount of friction. Near the lower end of the spindle a brass hub with four light arms is fixed by a set-screw, and each of these arms carries a rectangular aluminium vane; these vanes form a fan which retards the rotary motion of the spindle. Above the fan is a soft-iron ring fixed to the spindle by means of a corrugated aluminium disc, and it is upon this iron ring that the driving force is exerted by the current.

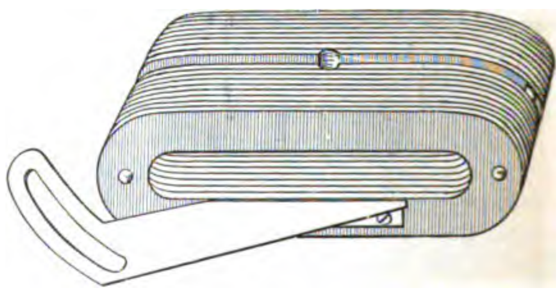
The coil through which the alternating current is passed is shown just below the counting mechanism in fig. 385. It is wound in two halves to allow space for the fan spindle to pass through it, and for a 20-ampere meter it would consist of 55 turns of No. 9 S.W.G. copper wire, double cotton-covered and varnished.

Fig. 386



the coil being taped over all. In the case of a 40-ampere meter, such as that illustrated, the coil consists of half the number of convolutions of considerably thicker wire; or the change from 20 to 40 amperes can be effected by joining the two halves of the coil in parallel. The current continually passes through this coil, but it would not by itself be competent to cause the rotation of the soft-iron ring which is placed inside it. In order to effect this, a second small coil is fixed inside the main coil, in such a way that both coils embrace the soft-iron ring, but the axis of one coil makes an angle of about 45° with that of the other. The second coil is illustrated in fig. 387, and in effect it consists of a single convolution of extremely low resistance. It is composed of 18 flattened 'rings' of sheet copper, held together by pins at each end, a small

FIG. 387



washer being placed between adjacent rings. The small arm, with the curved slot through which a set-screw passes, is for the purpose of clamping the coil in the exact position determined when the instrument is being calibrated.

Now when an alternating current is passed through the outer coil it magnetises the soft-iron disc, and the lines of force through the disc are reversed in direction with every reversal of the current; the magnetic axis is, however, always approximately in the same direction, viz. parallel to the axis of the outer coil. But the inner coil will also be acted upon by the outer coil; it will in fact act as the secondary coil of a transformer, and the alternating current which will be induced in it will lag about 90° behind the primary current—that is to say, its maximum will occur when the

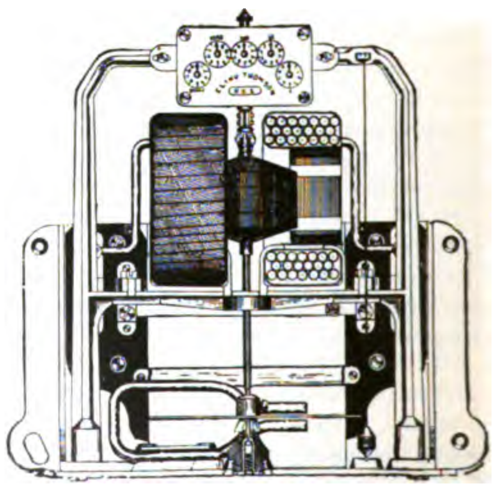
primary is at its minimum, and *vice versa.* This secondary current is of course not so powerful as it would be if an iron core or sheathing were employed and the axis of the two coils placed parallel, but it is nevertheless of considerable strength because of the extremely low resistance of the secondary coil. As the magnetisation of the iron disc lags somewhat behind the primary or main current, it will be seen that the induced currents in the closed secondary coil will continually tend to pull the disc round in the effort to make its lines of force coincide with those due to the current passing at that moment in the closed coil.

The instrument is enclosed in a sheet-iron cover, so that the resistance offered by the air to the fan is constant for any given speed, and the net result is that the number of revolutions made by the vertical spindle in any given time is proportional to the virtual amperes passing through the coil. In fig. 386 a small pointer will be seen on the top of the mechanism case; this pointer is carried by the first vertical spindle next to the vane spindle, and it is visible through a small glass window in the outer case. Its object is to enable the meter to be readily calibrated, or its accuracy to be checked at any time after it has been in use. A current of one ampere is passed through the instrument, and the number of revolutions indicated by this pointer in one minute is noted; the normal rate is about one per second, and, in the instrument illustrated, the pointer indicated exactly 60·3 revolutions in one minute. When this information has been obtained for any particular instrument, it is an easy matter to calculate the numbers of ampere-hours represented by the total number of revolutions as indicated by the four pointers, and then by multiplying by the normal pressure, the ampere-volt-hours can be estimated.

The motor meter invented by Professor Elihu Thomson gives the readings direct in watt-hours, and can be used either on a continuous or on an alternating current circuit without requiring to be recalibrated. It consists essentially of a small electric motor, the armature of which is carried on a vertical spindle. This armature consists of many convolutions of fine wire, which are wound on the drum principle, but without an iron core, and it is placed in series with a high non-inductive resistance, which is generally

fixed on a frame at the back of the meter. The armature with its resistance coil is connected between the positive and negative mains, so that the strength of the current flowing through the armature is determined by the potential difference of the circuit in which it is desired to measure the power expended. In fig. 388, which gives a view of the instrument with the cover removed and the right-hand half partly in section, it will be observed that there are two coils of thick wire overwound with tape, and partly embracing the armature; these coils are joined up in the main circuit, so

FIG. 388



that the full current passes through them, and they generate the field in which the armature rotates, being, like the armature, unprovided with iron cores. Since the current through the armature is determined by the pressure, and the field in which the armature rotates varies directly with the strength of the main current, it is evident that the torque or tendency to rotate the armature will at any instant be proportional to the product of volts and amperes, or, in other words, to the number of watts being expended in the circuit. In order to make the speed of rotation vary directly as the watts expended, a thin copper disc is fixed on to the vertical spindle

below the armature, and is embraced by the poles of two permanent steel magnets, one of which is shown in the figure. Immediately the disc begins to rotate in the powerful field produced by these steel magnets the eddy currents produced in the disc retard its rotation, and, as the strength of the eddy currents varies directly with the speed, the retardation is proportional to the speed, because the strength of the field is constant. It consequently follows, if there is no friction in the bearings or train-work, that the resultant speed will be directly proportional to the watts expended, and by means of the usual mechanism the number of revolutions made in any given time can be indicated by the five dials with which the instrument is provided. In some cases the number of revolutions is made to indicate directly the number of watt-hours, but generally a simple constant is provided, by which the number of revolutions must be multiplied in order to obtain the watt-hours. The calibration of the instrument can be readily effected by moving the poles of the permanent magnets either towards the centre or towards the periphery of the disc, and thus varying the retardation. The armature is provided with an eight-bar silver commutator, and the brushes, which consist of two rather long light springs, are fitted with silver contact-points. It is evident that however well the mechanism may be made, and however carefully the brushes may be adjusted, friction cannot be entirely avoided. This friction is compensated for by adding to the field coils some convolutions in series with the armature, and connecting the armature or pressure circuit to the mains on the lamp side of the series field coils; the feeble current thus continually flowing through the field coils, armature, and compounded coils is not quite sufficient to start the motor, but a start is effected with the slight increase of current obtained when even a feeble current passes through the mains to the lamp circuit, and the effect of friction is thus practically eliminated at low loads where it might introduce a considerable error.

An entirely different type of meter, which measures in ampere-hours, is that based upon the electrolytic properties of the current, and which possesses the advantage that no delicate mechanism need be employed in connection with it. It has already been explained that when a current is passed through a solution

containing a metallic salt the solution is decomposed, and the metal which it contained is deposited on the electrode by which the current *leaves* the liquid. Suppose, for example, a solution of nitrate of silver with silver electrodes to be employed, then pure silver would be deposited from the solution upon that electrode by which the current leaves. Moreover, an exactly equal quantity of silver would be dissolved from the other electrode. The solution, then, remains as rich in metal as it was before the passage of the current.

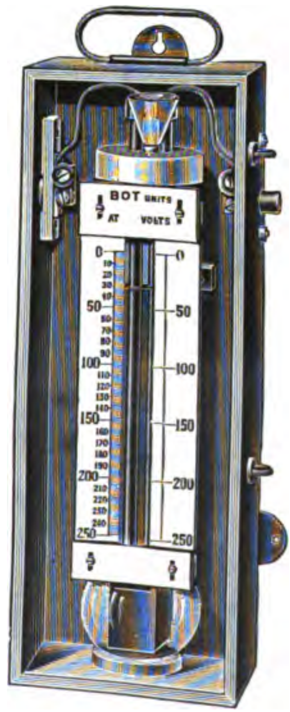
It is an important fact that the weight of metal deposited in this manner is exactly proportional to the quantity of electricity which has passed through the solution, irrespective, within wide limits, of the density of the solution or the strength of the current at any part of the time. It follows that after having ascertained the weight of any metal which is deposited by a coulomb of electricity, or by an ampere-hour of electricity, we can always calculate exactly the quantity of electricity which has been transferred on any occasion, provided we find out what weight of that metal the current has deposited. So long as the total quantity of current which passes is the same, it is immaterial whether the deposition is effected by a weak current flowing for a long time or a stronger current flowing for a correspondingly shorter time. Thus a current of half an ampere flowing for 48 hours will deposit the same weight of metal as a current of 16 amperes flowing for $1\frac{1}{2}$ hour; in either case the total quantity of electricity is 24 ampere-hours. It is necessary, however, to take care that the surface of the electrode shall be ample, otherwise the metal is deposited so rapidly on a small surface that it becomes granular, and does not adhere.

Several solutions have been utilised for electrolytic meters, such as copper sulphate, zinc sulphate, mercurous nitrate, and, more recently, mercuric nitrate, of which the last mentioned is the most satisfactory in its results.

Another type of electrolytic instrument is the **Bastian meter**, illustrated with the front removed in fig. 389. It consists essentially of a long moulded glass tube of uniform bore, enlarged into a bulb at its lower end. This tube is nearly filled with slightly acidulated water, a layer of paraffin oil being placed on the

surface of the water to prevent evaporation. The external conductors are connected to a pair of brass plates fixed inside the case near the top, and from these plates wires are led to and pass down a pair of vulcanite tubes. The wires are of lead (in order to protect them against oxidation) and the tubes containing them are screwed at their lower ends into a vulcanite frame, which serves the double purpose of supporting the tubes and keeping the platinum electrodes to which the lead wires are attached in position. As the current passes between the electrodes the water is decomposed, and, as we have already learned, the quantity of water so decomposed is directly proportional to the quantity of electricity or the number of coulombs transmitted. The oxygen and hydrogen gases which result from this decomposition rise to the top of the liquid as bubbles and pass thence into the air. Consequently the quantity of water contained by the tube is gradually reduced, and its level in the tube therefore falls. Manifestly the electricity passing through the meter can be indicated by measuring the fall of water. This is done by means of a scale placed in front of the tube. Each instrument requires, of course, to be carefully calibrated for any particular voltage, and then the instrument can be made to indicate in Board of Trade units. The white line in the figure (389) shows the division between the water and the paraffin, and indicates the consumption. Thus the consumption as registered by the illustration is 40 units. The quantity of gas liberated is too small to be in any way inconvenient or prejudicial, the combined volume of oxygen and

FIG. 389



hydrogen liberated in an hour by the passage of a current of 5 amperes being less than one-eighth of a cubic foot. As the resistance of the instrument is very low there is, for ordinary house installations, no need to use a shunt, the whole of the current passing through the water. There is obviously some advantage in this arrangement. The absence of any moving parts ensures that the instrument shall register exceptionally small loads; but of course the counter E.M.F. of water has to be overcome, and although on a 200-volt circuit this is not very serious, the consequences might be appreciable on a low-pressure circuit. The meters are made in a variety of sizes, to measure currents ranging from 1 to 80 amperes.

INDEX

[Every dash (—) stands for a word in the line preceding it.]